Review Article

Mechanisms of Metal Resistance and Homeostasis in Haloarchaea

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Received 26 October 2012; Revised 20 December 2012; Accepted 10 January 2013

Academic Editor: Elisabetta Bini

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Haloarchaea are the predominant microflora of hypersaline eoniches such as solar salterns, soda lakes, and estuaries where the salinity ranges from 35 to 400 ppt. Eoniches like estuaries and solar crystallizer ponds may contain high concentrations of metals since they serve as ecological sinks for metal pollution and also as effective traps for river borne metals. The availability of metals in these eoniches is determined by the type of metal complexes formed and the solubility of the metal species at such high salinity. Haloarchaea have developed specialized mechanisms for the uptake of metals required for various key physiological processes and are not readily available at high salinity, beside evolving resistance mechanisms for metals with high solubility. The present paper seeks to give an overview of the main molecular mechanisms involved in metal tolerance in haloarchaea and focuses on factors such as salinity and metal speciation that affect the bioavailability of metals to haloarchaea. Global transcriptomic analysis during metal stress in these organisms will help in determining the various factors differentially regulated and essential for metal physiology.

1. Introduction

Many metal ions have a key role in the physiology of cells. Metals such as calcium, cobalt, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, and zinc are essential and serve as micronutrients. These metals act as the redox centers for metalloproteins such as cytochromes, blue copper proteins, and iron-sulfur proteins which play a vital role in electron transport [1]. As the transition metals exist in numerous oxidation states, they efficiently act as electron carriers during redox reactions of electron transport chains to generate chemical energy [2, 3]. Metal ions also function as cofactors and confer catalytic potential and stability to proteins [4]. Other metals like silver, mercury, lead, aluminum, cadmium, gold, and arsenic have no biological roles and are potentially toxic to microbes [5]. The toxicity is exerted by the displacement of essential metals from native binding sites or through ligand interactions [6]. Both essential and nonessential metals at high concentrations disrupt cell membrane, alter enzymatic specificity, hinder cellular functions, and damage DNA [5]. Thus, as any disturbance in metal ion homeostasis could produce toxic effects on cell viability, the concentrations of metals within cells are stringently controlled. An increase in the ambient metal concentration leads to activation of metal resistance mechanisms to overcome metal stress. Metal homeostasis has been well studied in bacteria and eukaryotes and is attributed to differential regulation of transporters like P$_{1B}$-type ATPases, ABC transporters, cation diffusion facilitators (CDFs), and metallochaperones in response to metals [7–9]. Among the Archaea, thermophiles and hypervermophilies of the Crenarchaeota and the methanogens and thermophilies of the Euryarchaeota utilize P$_{1B}$-type ATPases and ABC transporters for metal transport and homeostasis [10, 11]. However, metal homeostasis in haloarchaea from the phylum Euryarchaeota has not been extensively studied [11]. Haloarchaea are members of the third domain of life, the Archaea, within which a total of 36 genera and 129 species have been identified to date [12]. These organisms require between 10% and 35% salt for optimum growth and are the predominant microflora of hypersaline environments such as solar salterns, salt lakes, soda lakes, salt deposits, and so
2. Bioavailability of Metals to Haloarchaea

For a metal to act either as a micronutrient or as a toxicant, it has to be available for uptake by the organism [27]. The metal species determines the solubility, bio-availability, and membrane transport, besides influencing the phenomenon of adsorption, oxidation/reduction, and oceanic residence times [28]. Metal speciation is governed by alkalinity, pH, hardness (presence of Ca/Mg), natural dissolved organic matter, redox potential, and salinity [29]. Strongly complexed and thus nonlabile and particulate metal species are less available to organisms for uptake [30]. As haloarchaea inhabit hypersaline environments with salinity in the range of 2%–35%, salinity is proposed to be the most important factor affecting bio-availability. The salt content in hypersaline eoniches of solar salterns is about 10-fold of its concentration in seawater [31] due to evaporation. This process also concentrates other anions and cations present in the sea water including the metal salts fed through contaminated estuaries [32]. The high chloride ion (Cl−) content in these environments results in the formation of metal chlorocomplexes.

The type of complex formed depends upon the chelating ligand, that is, organic or inorganic ligands, and the kind of heavy metal present in the system [33]. Metals like Zn and Cu that have small ionic radii preferentially complex with hard donors containing oxygen like OH−, CO32−, HCO3−, and SO42− to form inorganic complexes [34]. Soft acceptors like Hg, Cd, and Ag are easily ionized and are thus, more likely to form chlorocomplexes. Although inorganic species exist in natural waters, organic metal species predominate [35]. The complexion of metals with organic ligands reduces bioavailability as organic-metal complexes are not readily transported across cell membranes [30, 36]. Inorganic species, on the other hand, are readily available to the biota as the complexes are weak and dissociate rapidly to form free ions which bind to the transporters or are chelated by biotic ligands secreted by the organisms [37–40]. Table 1 shows the type of inorganic species formed at different salinities for five major metals.

While metal bio-availability, uptake, and toxicity decrease in presence of natural dissolved organic ligands, metals differ in their behavior at high salinities. For example, in case of cadmium, speciation is highly dependent on the complexing ligands. In river water it exists either as CO32− complex or free cation, and in oceanic waters it exists as highly soluble CdCl2, whereas in estuarine waters, it forms a strong CdCl+ complex which is biologically unavailable [41–43]. In case of silver, insoluble AgCl0 is formed in estuarine and oceanic waters, while under hypersaline conditions, soluble AgCl2−, AgCl3−, and AgCl4− complexes are formed [44]. Soluble HgCl+ and sparingly soluble HgCl2 are the predominant complexes of Hg at high salinities [45]. HgCl2 and the soluble silver-chloro complexes are lipophilic and can easily diffuse through cell membranes [46]. Zn and Cu exist as ZnCl+ and CuCl+ which coprecipitate at higher salinities, due to decrease in the net negative charge on macromolecular suspended particles and therefore are not available for uptake. Unlike Zn(II) and Cu(II), Fe(II), Co(II), Ni(II), and Mn(II) form weak complexes with Cl−, that easily dissociate and can be taken up by organisms [28]. Table 2 summarizes the bioavailability of metal-chloro complexes.

The bioavailability of chlorocomplexes also depends upon the type of biotic ligands present. Biotic ligands are the receptors on an organism where metal binding takes place which results in the manifestation of its toxic effects [47]. Metal receptors and ion transporters such as Na(II) and Ca(II) transporters present on fish gill surfaces, algal membranes, phytoplankton membranes, and so forth act as biotic ligands [47]. Binding of metals to biotic ligands is unaffected by changes in salinity. However, metal complexes adsorbed to abiotic ligands such as sediments are desorbed with increase in salinity. Thus, biotic ligands render the metals unavailable to other organisms for uptake. For example, in case of silver, with increase in salinity, desorption of Ag(I) complexed with
Table 1: Various inorganic complexes formed in natural waters, seawater, estuarine waters (variable salinity), and hypersaline waters. As haloarchaea inhabit hypersaline environments where inorganic ligands predominate, inorganic metal speciation is described. The availability of metal depends upon the kind of inorganic complex formed. Lipophilic soluble chlorocomplexes of Hg and Ag are easily available in hypersaline waters. Insoluble (precipitated) ZnCl₂ and CuCl₂ are unavailable to the organism. Fe(II), Co(II), Ni(II), and Mn(II) form weak complexes with Cl⁻ that easily dissociate and can be taken up by organisms [28, 41–46].

| Metal | Hypersaline (5–35% salinity) | Sea water (3.5% salinity) | Estuarine (variable salinity) | River water/natural water |
|-------|-----------------------------|---------------------------|-----------------------------|---------------------------|
| Cd    | CdCl₂, CdCl⁺                 | CdCl⁺                     | CdCl₂, CdCl⁺                | Cd²⁺, CdCO₃               |
| Ag    | AgCl⁺, AgCl₂⁻, AgCl₃⁻², AgCl₄⁻³ | AgCl⁺, AgHS⁻³, AgCl₂⁻, AgCl₄⁻³ | AgCl⁺, AgHS⁻³, AgCl₂⁻, AgCl₄⁻³ |
| Hg    | HgCl₂⁻, HgCl⁻                 | HgCl⁻                     | HgCl₂⁻, HgCl⁻                | Mixture of Hg-chloro and hydroxy complex |
| Zn    | ZnCl₂                        | Zn²⁺, ZnCl₁, ZnCO₃, Zn(HCO₃)₁, Zn(OH)₂, ZnSO₄ | Zn²⁺, ZnCl₁, ZnCO₃, Zn(HCO₃)₁, Zn(OH)₂, ZnSO₄ | Hydrated Zn²⁺ |
| Cu    | CuCl₂                        | Carbonato and hydroxy complexes | CuCl₂, Carbonato and hydroxy complexes | Cu²⁺, CuCO₃ |

Table 2: Bioavailability of metal-ligand complexes in hypersaline conditions depending upon the nature of the complex formed.

| Availability | Type of complex |
|--------------|-----------------|
| Biologically unavailable | (i) Strong insoluble inorganic metal-chloro complexes (ZnCl₂, CuCl₂) |
|                  | (ii) Soluble not easily dissociable metal-chloro complexes (CdCl₂) |
|                  | (iii) Biosorbed metal complexes (i.e., metals sorbed on a biotic ligand) |
| Biologically available | (i) Strong soluble lipophilic inorganic metal-chloro complexes (AgCl⁺, AgCl₂⁻, AgCl₃⁻, and HgCl₂) |
|                  | (ii) Weak metal-chloro complexes (Fe, Co, Ni, and Mn) |
|                  | (iii) Metal complexes sorbed to abiotic ligands |

suspended sediments and formation of soluble chlorocomplexes, which are bioavailable have been observed. However, biosorbed Ag(I) is not influenced by the increase in salinity, and desorption of Ag(I) does not occur [48].

The toxicity of a metal to microorganisms does not have a linear relationship with its concentration, and it depends strongly upon chemical speciation [49, 50]. For certain metals such as Zn(II) and Cu(II), complexation with chloride ions may result in precipitation at high salinities. Therefore, these complexes are not available to micro-organisms for uptake. However, metals such as Hg(II), Ag(II), Fe(II), Co(II), Ni(II), and Mn(II) either form lipophilic soluble chlorocomplexes or weak chlorocomplexes that dissociate easily and are thus available to organisms for uptake. Therefore, while studying metal resistance in haloarchaea, metal speciation and the bioavailability of metals should be taken into consideration.

3. Metal Resistance

Organisms inhabiting the metal polluted environments develop resistance mechanisms that enable efficient detoxification and transformation of toxic forms to nontoxic forms. The majority of bacteria and eukarya tolerate metals by a reduced influx/enhanced efflux [51, 52] or enzymatic detoxification sometimes followed by volatilization [6, 53]. Intracellular compartmentalization is observed only in eukaryotes [51]. Figure 1 shows the various mechanisms of metal resistance exhibited by all the three domains of life.

Intracellular chelation (Figure 1) by a variety of cysteine-(Cys-) rich metal-binding peptides like glutathione (GSH) and proteins like metallothioneins (MTs) and phytochelatins (PCs) also confers resistance to metals in many microbes [54]. MTs are genetically coded small molecular weight polypeptides that are classified based upon the number of Cys residues [55]. They typically have two Cys-rich domains that bind heavy metals through mercaptide bonds, giving these proteins a dumbbell-shaped conformation comprising an N-terminal β-domain that usually binds 3 metal ions and a C-terminal α-domain that binds 4 metal ions [56, 57]. PCs comprise (γ-GluCys)ₙ-Gly where n is usually in the range of 2 to 5. They are enzymatically synthesized by PC synthase using GSH as the substrate [58, 59]. The thiol group of the cysteine residue in PCs sequesters heavy metals. Apart from these cysteine-rich peptides, cells may secrete other metal sequestering proteins like siderophores and DNA-binding protein from nutrient starved cells (Dps).
Figure 1: General mechanisms adapted by bacteria, eukaryotes, and archaea for metal resistance. All the three domains exhibit sorption of metals, volatilization, release of metal chelating compounds in the medium, enhanced efflux, impermeability, decreased uptake, enzymatic detoxification, and intracellular chelation as mechanisms for metal resistance. Organellar compartmentalization is observed only in eukaryotes, with the exception of magnetosomes in magnetotactic bacteria.

(Figure 1). Siderophores are a class of low molecular weight iron chelating compounds which store iron and are overexpressed during conditions of stress or iron deficiency [60]. They are chemically diverse and generally possess oxygen-donor-type chelating functional groups [61]. Once chelated, the Fe-siderophore complex is transported to the periplasm through the energy-coupled transport involving TonB dependent transporters (TBDT) and the inner membrane TonB-complex, composed of TonB, ExbB, and ExbD. The Fe-siderophore can then be transported to the cytoplasm through ABC transporters like ferrichrome or permeases [62]. TonB protein is responsible for transducing cytoplasmic membrane energy to the outer membrane which results in the release of metal chelating agents into the medium.

Haloarchaea have γ-glutamylcysteine (γ-GC) [67, 68] which is analogous to GSH and is involved in maintaining a reducing environment within the cell, overcoming oxidative and disulfide stress and detoxification of xenobiotics [69]. The thiol group of cysteine in γ-GC can chelate the toxic metal ions thereby conferring resistance. A unique phenomenon observed in archaea is the heavy metal-induced multimerization of metal chelating proteins such as CutA- and DpsA-like proteins that result in the precipitation of the protein-metal ion complex [23]. This precipitate resolubilizes and the multimers disintegrate when the metal stress decreases [70, 71]. Although these proteins are known to be involved in divalent metal tolerance in bacteria and eukaryotes, the multimerization of these proteins has been observed only in archaea. The aspartate residue in position 48 has been found to be critical for metal-induced multimerization and metal ion binding of CutA protein in Pyrococcus horikoshii. Substitution of Asp48 with alanine decreases the amount of aggregate formation [70]. Similarly, the multimeric non-haem ferritin DpsA-like protein of Halobacterium salinarum ensues from an assembly of 12 units and was found to sequester iron in response to the oxidative stress exerted by excess iron [72]. This protein was downregulated under iron-deficient conditions unlike the other dps that are upregulated under these conditions. It exhibits the features of non-haem bacterial ferritins that are expressed to sequester the excess iron. Their expression is repressed under conditions of iron starvation [73]. Overexpression of siderophores in haloarchaeae may increase chelation in case of iron deficiency. On the other hand, repression of these siderophores in presence of excess iron may avoid uptake [68, 74]. MTs are absent in archaea [23].

Biosorption of metals by the organisms at the surface or by the exopolysaccharides (EPS) secreted to form the biofilms enables organisms to tolerate metals [75, 76].
Archaea

forming organisms exhibit an altered phenotype with respect to growth rate and gene transcription [77]. Haloarchaea synthesize EPS as a protective mechanism for survival under adverse conditions such as nutrient starvation, temperature fluctuation, and presence of toxic compounds [78]. Similarly, the hyperthermophilic archaeaeon, *Archaeglobus fulgidus*, was found to form a biofilm in response to toxic concentrations of metals, where the toxic metal was proposed to be trapped within the EPS matrix [78]. Thus, it is probable that under metal stress, haloarchaea may secrete EPS to make the cell impermeable to metals. In a study by Kawakami et al. (2007) [79], it has been found that *Halobacterium salinarum* CCM 2090 has a Ca(II)-dependent aggregation system, where the Ca(II) binds to certain aggregation factors present on the cell surface and induces ionic crossbridging between the EPS resulting in aggregation of the haloarchaeal cells. The presence of certain receptor proteins on the cell surface that interact with Ca(II) to form cell aggregates/flocs has also been demonstrated [79]. Four haloarchaeal genomes, *Haloquadratum walsbyi*, *Haloarcula marismortui*, *Haloterrigena turkmenica*, and *Halobacterium* sp. strain NRC-1, have been annotated with *cbp* encoding the cell surface calcium-binding acidic-repeat protein [80–83] that has been proposed to be the factor involved in Ca(II)-dependent aggregation, although its role in this process remains to be demonstrated. A similar dependence on Ca(II) and/or Fe(II) for biofilm formation is observed in *Vibrio cholerae* [84] and *Pseudomonas aeruginosa* [85]. Ca(II) is the twentieth element in the periodic table and induces cell surface adhesion, and motility [91]. Archaeal type IV pili have been shown to be involved in biofilm formation by *Haloferax*, *Halobacterium*, and *Halorubrum* [87, 92, 93]. The biofilm formed may trap the metals within the EPS matrix and prevent the diffusion of metals inside the cell, thus conferring resistance to haloarchaea.

Most bacteria carry the resistance determinants for metals as operons, on their plasmids [94]. The metal resistance operons usually include genes for transporters and an enzyme for detoxification. Haloarchaea exhibit resistance mechanisms similar to those of bacteria. The *ars* operon conferring arsenite and arsenate resistance in *Halobacterium* sp. strain NRC-1 is present on one of its two plasmids [83]. A comparative genome analysis of bacteria and archaea revealed some common elements responsible for maintenance of metal homeostasis and resistance. *P* _{1B} -type ATPases involved in cation transport with a high diversity in the N-terminal metal-binding motifs were found to be distributed throughout the bacterial and archaeal lineages [10]. Genome of *Halobacterium salinarum* NRC-1 was found to carry two distinct phylogenetic clusters, CopA1 (Cu(II) influx) and CopA2 (Cu(II) influx and eflux). These clusters were also found to span the entire diversity of the bacterial domain. Coombs and Barkay (2005) [10] have proposed that variation in N-terminal metal-binding motifs does not affect the metal translocation function of *P* _{1B} -type ATPases and therefore concluded that divergence in consensus sequence of the N-terminal metal-binding motif might have been tolerated during evolution [10, 83]. But this is just one of the few studies on metal homeostasis in archaea. Similar studies understanding the phylogenetic variation within the family Halobacteriaceae will enable a better understanding of metal homeostasis, by giving a snapshot of substrate specificity, variation in active sites, and so forth [23].

3.1. Operons in Metal Resistance. Many metal resistance determinants have been characterized in the bacterial system [95–105], of which *mer* operon for mercury resistance [95], *ars* for arsenic resistance [97, 98], and *cad* operon for cadmium resistance [99] have been extensively studied. All archaea except haloarchaea have been shown to carry such metal resistance determinants [106, 107]. The most comprehensively studied among these are the *mer* operon of the thermoacidophilic archaeon *Sulfolobus solfataricus* [108, 109], *ars* operon of acidophilic archaeon *Ferroplasma acidarmanus* Fert [110] and *Thermoplasma acidophilum* [111], and the *cop* operon for copper resistance of *Sulfobolus solfataricus* P2 [112–114]. Although many heavy metal transporters like CbiNOQ, HemUV, NosF, and so forth are present in haloarchaeae, their arrangement in an operon has not been shown, except for the ArsA ATPase transporter as a part of *ars* operon for arsenic resistance in *Halobacterium* sp. strain NRC-1 [21].

Most haloarchaeae have large plasmids in addition to their genomes (chromosomes) known as minichromosomes/megaplasmids. These minichromosomes harbor genes for antibiotic resistance or metal resistance that may be essential for haloarchaeal survival [115]. The pNRC100, one
of the two minichromosomes of model organism *Halobacterium* sp. strain NRC-1, harbors the *arsADRC* gene cluster, responsible for conferring arsenate (As(V)) and arsenite (As(III))/antimonite (Sb(III)) resistance [83]. A fifth gene for arsenic resistance, *arsB*, is present on the main chromosome. The *arsADRC* operon was annotated for As(III) transport due to its homology to previously characterized genes [116], but later, by gene knockout studies, it was shown to confer resistance to As(III) and Sb(III) [21]. As(V) can be taken up by the cells through phosphate transporters (pit/pst) and As(III) by aquaglyceroporins (glycerophorin membrane transport proteins) [117] or hexose transporters [118]. As(V) is then converted to As(III) by arsenate reductase encoded by *arsC* [119]. *arsA* codes for P_{1B}-type ATPase transporters that help in extrusion of As(III)/Sb(III) from the cell. *arsR* and *arsD* encode trans-acting repressors of the operon. *ArsR* and *ArsD* bind to As(III)/Sb(III) resulting in expression of the *arsA* and *arsC*. Arsenate reductase encoded by *arsC* is expressed weakly in *Halobacterium* sp. strain NRC-1, and therefore deletion of *arsC* and *arsADRC* was found to be ineffective in conferring arsenate sensitivity [21]. The operon *arsADRC* was found to be inducible by arsenite and antimonite [21].

In bacteria, *ArsB*, an inner membrane protein, along with *ArsA*, the membrane-bound anion-transporting ATPase, forms the anion-conducting channel for arsenite extrusion [120]. *Halobacterium* sp. strain NRC-1 also harbors both *ArsA* and *arsB* in the megaplasmid pNRC100 and *arsB* on the main chromosome. However, *arsB* was found to play no role in arsenic resistance in this organism. Thus, it has been proposed that *Halobacterium* sp. strain NRC-1 harbors a novel transporter unrelated to *ArsB* but with a similar function [21]. Arsenic resistance in the Gram-negative acidophilic bacterium Acidithiobacillus ferrooxidans is determined by the chromosomally located *arsCRBH* operon comprising four genes [121]. The unique and common feature between the *arsADRC* and *arsCRBH* operons is the bidirectional nature of translation; that is, the *arsAD* and *arsCR* genes are translated in an opposite direction to *arsRC* and *arsBH*, respectively [21, 121] (Figure 2).

In *Halobacterium* sp. strain NRC-1, a second arsenite resistance operon, *arsR2M*, is present upstream of *arsADRC* on pNRC100 (Figure 2), where *arsR2* is constitutively expressed while As(III)/Sb(III) induce the expression of *arsM* [21]. The *arsR2* is analogous to *arsR* and *arsM* encodes a putative As(III)-methyltransferase very similar to human methyltransferases and S-adenosyl methionine-dependent methyltransferases of *Magnetospirillum magnetotacticum*. *ArsM* is involved in converting As(III) to methylated species like dimethylarsinate (DMA), trimethylarsine oxide (TMAO), or trimethylarsine (TMA) gas [122]. Deletion of *arsM* exhibited as increased sensitivity to arsenite but not towards arsenate or antimonite [21]. Thus, two possible mechanisms of As(III) resistance have been proposed to be conferred by *arsM*. First, the generation of a concentration gradient results in the movement of methylated arsenite (negatively charged/uncharged) out of the cell. Second, the volatile trimethylarsine formed diffuses out of the cell thus eliminating As(III) [123, 124]. Although arsenite methylation as a resistance mechanism is present in bacteria, *arsM* gene functions independently and is not a part of *ars* operon [123]. However, in *Halobacterium* sp. strain NRC-1, the *arsM* gene is present as a part of the *arsR2M* operon involved in arsenite resistance [21].

Mercury resistance in archaea and bacteria is conferred by the *mer* operon involved in detection, regulation, transport, and reduction of Hg(II) [125, 126]. One of the best studied mercury resistance operons in Archaea is the *merRHA1* operon of thermoacidophilic archaeon *Sulfolobus solfataricus* [108, 109]. The operon is under the control of the regulator MerR, which represses the operon in absence of Hg(II) and enhances transcription in its presence. MerH is the mercurichaperone with a TRASH (trafficking, resistance, and sensing of heavy metals) domain that binds Hg(II), and MerA is the mercuric reductase for reduction and detoxification to volatile Hg(0) [108, 109]. Some *mer* operons carry additional *mer* genes, notably *merB*, an organomercurial lyase, that cleaves the C-Hg bonds of organomercurials, and the released Hg(II) is reduced to Hg(0) by MerA [126]. Among all haloarchaeal genomes sequenced to date, only *Halobacterium* sp. strain NRC-1 and *Haloterrigena turkmenica* have been annotated with *merA* and *merB* genes, respectively [83, 127].

### 3.2. Transporters in Metal Resistance.

Membrane transporters may act as the first line of defense against toxic or heavy metals. In order to exert their toxicity, metals need to gain entry within the cell. Thus, the organism may downregulate the transporters responsible for influx or induce the expression of efflux pumps to enable faster removal of toxic metals from within the cell [76]. The use of these membrane transporters and efflux pumps is one of the most common mechanisms of resistance to inorganic ions in microbes.

Both influx and efflux types of transporters for various metals have been annotated in all haloarchaeal genomes sequenced to date (Table 3). The following membrane transporters have been implicated in haloarchaeal metal resistance.

#### 3.2.1. P_{1B}-Type ATPases.

The P_{1B}-type ATPases are a large family of integral membrane proteins driven by ATP hydrolysis [128]. Members of this family are of vital importance to all kingdoms of life, as they generate and maintain electrochemical gradients across membranes by transporting cations and heavy metals [129]. A wide variety of heavy metal ions like Mg(II), Ca(II), Cu(II), Ag(II), Zn(II), and Cd(II) act as substrates to these ATPases [130]. These transporters serve the purpose of uptake (import) of essential elements and efflux (export) of toxic elements, thus conferring resistance to the expelled metal ion [131, 132]. All haloarchaeal genomes have been annotated with metal transporting ATPases.

A putative Cd(II)-efflux ATPase was annotated on *Halobacterium* sp. strain NRC-1 genome [83]. In a system level analysis of *Halobacterium* sp. strain NRC-1, the functionality and role of such transporters in metal resistance was shown [22]. They exhibited upregulation of *yvgX*, a P_{1B}-type ATPase, in response to Cu(II) and Zn(II) metal stress. In bacteria, the *yvgX* family is known to encode two kinds of CopA
Figure 2: Arsenic resistance is determined by the presence of ars operon, which codes for an arsenite P$_1$-type ATPases transporter ArsA/ArsB, an arsenate reductase ArsC, and arsenite responsive repressors ArsD and ArsR. The arsADRC and arsR2M operons are present on the plasmid in haloarchaeon *Halobacterium* sp. strain NRC-1 (a). The acidophilic bacterium *Acidithiobacillus ferrooxidans* has chromosomally encoded arsCRBH (b). The unique feature of these operons is the bidirectional nature transcription.

Table 3: Annotated transporters for various metals in haloarchaeal genomes. Ten haloarchaeal genomes have been completely sequenced while others are partially sequenced. All these organisms have been annotated with transporters belonging to the following type of transporters—cation efflux type, P$_1$B-type ATPases, cation diffusion facilitator (CDF) family, and ATP-binding cassette (ABC) family. The most abundant transporters were for iron followed by copper. Only one haloarchaeon, *Halogeometricum borinquense*, was annotated with silver transporters [135].

| Transporters for metals | H.s. | H.m. | H.v. | H.w. | H.l. | H.mu. | H.u. | H.b. | H.t. | H.j. | N.p. | N.m. |
|-------------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| Copper                  | +    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Iron                    | +    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Manganese               | -    | +    | +    | +    | +    | -    | -    | +    | -    |         |      |      |
| Zinc                    | +    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Cobalt                  | +    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Nickel                  | +    | -    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Molybdenum              | -    | +    | +    | +    | +    | -    | -    | +    | -    |         |      |      |
| Arsenic                 | +    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Cadmium                 | +    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Magnesium               | -    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |
| Silver                  | -    | +    | +    | +    | +    | +    | +    | +    | +    |         |      |      |

(+): present; (−): not annotated yet; *H.s.*, *Halobacterium* sp. strain NRC-I; *H.m.*, *Halocarcula marismortui*; *H.v.*, *Haloferax volcanii*; *H.w.*, *Haloquadratum walsbyi*; *H.l.*, *Halorubrum lacusprofundi*; *H.mu.*, *Halomicrobium mukohataei*; *H.u.*, *Halorhabdus utahensis*; *H.b.*, *Halogeometricum borinquense*; *H.t.*, *Haloterrigena turkmenica*; *H.j.*, *Halalkalicoccus jeotgali*; *N.p.*, *Natronomonas pharaonis*; *N.m.*, *Natralba magadii*.

proteins, CopA1 and CopA2 [133]. CopA1 is essential for copper influx and tolerance, while CopA2 is involved in the influx/efflux of Cu and its transport to Cu-containing enzyme cytochrome oxidase c [133, 134]. A diverse range of organisms contain CopA2-like proteins, suggesting that coding genes appeared early in evolution via gene duplication or horizontal transfer but were kept only in some organisms for a specific biological function [134]. A comparative genome analysis for ATPases in bacteria and archaea showed the preference for CopA2 over CopA1 [10]. It has been proposed that CopA2 may represent the ancestral form of CopA1 protein that may have coevolved with the other metal influx proteins [10]. The yvgX of *Halobacterium* sp. strain NRC-1 was found to be more specific for Cu(II) efflux family as the ΔyvgX strain was susceptible to Cu(II) and not to Zn(II) or Co(II) and therefore belongs to the CopA2 family of proteins. CopA2 is also found in other haloarchaea like *Halocarcula marismortui*, *Halocarcula hispanica*, and *Haloquadratum walsbyi* [135].

The As(III)/Sb(III) transporting P$_{1B}$-type ATPase, ArsA discussed in Section 3.1, is present in almost all haloarchaea sequenced to date, including *Halobacterium* sp. strain NRC-1, *Halalkalicoccus jeotgali*, *Halocarcula hispanica*, *Natralba magadii*, *Halocarcula marismortui*, *Haloquadratum walsbyi*, and *Natronomonas pharaonis* [135]. ArsB was found to play
no role in arsenite resistance in *Halobacterium* sp. strain NRC-1 [21].

Heavy metal cation-transporting CPx P$_{1B}$-type ATPases are of two types, that is, Cu-CPx-type ATPases involved in efflux of monovalent cations, Cu(I) and Ag(I), and Zn-CPx-type ATPases involved in the efflux of divalent cations of Zn, Cd and Pb [137–139]. However, Cu-CPx-type ATPases have also been shown to be involved in uptake of copper to meet cellular demands [140, 141]. The cpx gene that encodes CPx P$_{1B}$-type ATPases was found to be downregulated by Fe(II), Cu(II), and Ni(II) to avoid influx in *Halobacterium* sp. strain NRC-1 [22]. This mechanism of resistance involving the downregulation of uptake systems avoids toxic metal buildup within the cell.

3.2.3. ATP-Binding Cassette (ABC) Transporters. The ABC family of transport proteins is ubiquitous present in all three domains of life [142]. Although ABCs are primarily Zn(II) efflux pumps, bacterial ABCs have been shown to transport Hg(II), Pb(II), Zn(II), Co(II), Fe(II), and Cd(II) from the cytoplasm to the outside of the cell or into subcellular compartments [132, 143]. Based upon their substrate specificity, ABCs have been classified as Zn(II)-CDF, Fe/Zn-CDF, and Mn-CDF [144]. They usually possess six transmembrane domains (TMDs) with a cytoplasmic N- and C-terminal and a histidine loop of variable length between TMD IV and V [145, 146]. The amphipathic domains TMD I, II, V, and VI are involved in metal transfer and are the most conserved, while the hydrophobic TMD III and IV are critical for zinc specificity and mutations within these domains alter substrate specificity [144]. All the proteins of this family of transporters possess a characteristic cation efflux C-terminal domain [147]. These kinds of transporters serve as secondary cation filters in bacteria [132]. The genome of *Halobacterium* sp. strain NRC-1 was annotated with putative CDF Cd (II) transporter ZntX, which confers resistance against Ni(II), Cu(II), and Zn(II) besides Cd(II) [22]. The role of Znt family of CDFs in Cu(II) and/or Zn(II) homeostasis and resistance has been discussed in detail by Haney et al. (2005) [145]. The upregulation of ZntA in response to heavy metals (Cu and/or Zn) and poor growth of ΔzntA strain in presence of Ni(II), Cu(II), Zn(II), and Cd(II) have confirmed the role of this transporter in metal resistance [22]. The broad specificity of this transporter has been putatively attributed to the preference of metals by zntA based on charge and species rather than size [148]. *Haloarcula hispanica* and *Haloarcula marismortui* have also been annotated with ZntA for Zn(II) transport. A putative CDF family protein has also been found on the chromosome of *Natrialba magadii* for inorganic metal ion transport [135].

3.2.2. Cation Diffusion Facilitators (CDF Family) Metal Transporters. The CDF family of transport proteins is ubiquitously present in all three domains of life [142]. Although CDFs are primarily Zn(II) efflux pumps, bacterial CDFs have been shown to transport Hg(II), Pb(II), Zn(II), Co(II), Fe(II), and Cd(II) from the cytoplasm to the outside of the cell or into subcellular compartments [132, 143]. Based upon their substrate specificity, CDFs have been classified as Zn(II)-CDF, Fe/Zn-CDF, and Mn-CDF [144]. They usually possess six transmembrane domains (TMDs) with a cytoplasmic N- and C-terminal and a histidine loop of variable length between TMD IV and V [145, 146]. The amphipathic domains TMD I, II, V, and VI are involved in metal transfer and are the most conserved, while the hydrophobic TMD III and IV are critical for zinc specificity and mutations within these domains alter substrate specificity [144]. All the proteins of this family of transporters possess a characteristic cation efflux C-terminal domain [147]. These kinds of transporters serve as secondary cation filters in bacteria [132]. The genome of *Halobacterium* sp. strain NRC-1 was annotated with putative CDF Cd (II) transporter ZntX, which confers resistance against Ni(II), Cu(II), and Zn(II) besides Cd(II) [22]. The role of Znt family of CDFs in Cu(II) and/or Zn(II) homeostasis and resistance has been discussed in detail by Haney et al. (2005) [145]. The upregulation of ZntA in response to heavy metals (Cu and/or Zn) and poor growth of ΔzntA strain in presence of Ni(II), Cu(II), Zn(II), and Cd(II) have confirmed the role of this transporter in metal resistance [22]. The broad specificity of this transporter has been putatively attributed to the preference of metals by zntA based on charge and species rather than size [148]. *Haloarcula hispanica* and *Haloarcula marismortui* have also been annotated with ZntA for Zn(II) transport. A putative CDF family protein has also been found on the chromosome of *Natrialba magadii* for inorganic metal ion transport [135].

3.3. Transcriptional Changes in Response to Metal Stress. Under unfavourable conditions of growth, all organisms make adjustments at the system level to overcome the stress imposed by the stressor. Presence of heavy metals in their environment triggers global transcriptional regulations either to prevent their entry into the cell or to transform the metal to nontoxic form. This response can be transitory, with perturbations of a few genes within minutes of metal exposure, but once the cell acclimatizes to the new environment, the transcript levels of some early response genes return to preperturbation levels. The early response to a stressor usually results in the upregulation of transcription and translation. As a consequence, the transcripts damaged due to the stressor are replaced and new proteins are synthesized [161, 162].

In haloarchaea, only one study on transcriptional changes in response to heavy metal stress (Fe(II), Cu(II), Co(II), Ni(II), Zn(II), and Mn(II)) in *Halobacterium* sp. strain NRC-1 has been reported [22]. Besides studying the transcriptional and protein transport [150], metal extrusion [151, 152], and drug efflux [153, 154]. Although many ABC transporter genes for a variety of substrates have been annotated in all the 10 haloarchaeal genomes sequenced to date, experimentally, very few have been shown to be functional. ABC transporters for sugar and polypeptide have been found in *Halofex volcanii* [155], *Halorocaula marismortui* [81], *Halobacterium sp.* NRC-1 [83], *Natronomonas pharaonis* [156], and *Haloquadratum walsbyi* [80]. All haloarchaea possess at least one copy of metal ion ABC transporter. Some of the ABC transporters in *Halobacterium* sp. NRC-1 with their functions are listed in Table 4. Many of the ABC transporters are metal ion transporters such as *cblNOQ* for Co(II) transport [157], *hemUV* for iron uptake [158, 159], *nosFY* for copper [160], and *zurMA* for zinc transport (Figure 3). Although most of the ABC transporter proteins exhibit stringent specificity towards their substrate, a few, such as phosphate transporters, oligopeptide transporters, and dipeptide transporters, have been shown to have multiple specificities and were found to be differentially regulated by more than one metal ion. This has been proposed to facilitate transport of metal ions in addition to their usual function [150]. Kaur et al. (2006) [22] have shown that deletion of transporters like *phaX* (phosphate transport), *appA* (peptide transport), and *ycdH* (Mn(II) transport) along with two putative subunits of Fe(II) transport system does not prove deleterious for *Halobacterium sp.* NRC-1. Due to the large repertoire of ABC transport proteins, they concluded that deletion/mutation of a single ABC transporter is easily managed by the organism by substituting the deleted/mutated ABC transporter product with functional ABC transporter product of similar role.

The differential regulation of all three classes of metal transporters discussed above is in congruence with the general norm of micro-organisms utilizing enhanced efflux or decreased influx to resist metals. However, the P$_{1B}$-type ATPases and CDF family have a greater role in maintaining metal homeostasis than the ABC transporters in haloarchaea [22].
Table 4: ABC transporters with various functions present in some model haloarchaea. ABC transporters have three components that together help in uptake of nutrients or for the efflux of extracellular proteins, enzymes, and toxicants. Permease is the transmembrane component and is responsible for the uptake of ions or macromolecules, while the ATP-binding component is the water-soluble domain that binds ATP. Substrate binding at the substrate binding site brings about a conformational change in the ATP-binding component resulting in ATP hydrolysis. The presence or absence of the three components of ABC transporters for sugar, peptide, amino acids, phosphate, and iron transport is shown in the following table [135, 136].

| ABC transporters                      | H.s. | H.v. | H.m. | H.w. | H.l. | N.p. | N.m. |
|---------------------------------------|------|------|------|------|------|------|------|
| Sugar transport system components     |      |      |      |      |      |      |      |
| Permease                              | +    | +    | +    | +    | −    | −    | −    |
| ATP binding                           | +    | +    | +    | +    | −    | −    | −    |
| Substrate binding                     | −    | −    | −    | +    | +    | +    | +    |
| Phosphate transport system components |      |      |      |      |      |      |      |
| Permease                              | +    | +    | +    | +    | −    | −    | −    |
| ATP binding                           | −    | +    | +    | +    | +    | +    | +    |
| Substrate binding                     | +    | +    | +    | +    | +    | +    | +    |
| Dipeptide/oligopeptide transport system components |      |      |      |      |      |      |      |
| Permease                              | +    | +    | +    | +    | −    | −    | −    |
| ATP binding                           | +    | +    | +    | +    | −    | −    | −    |
| Substrate binding                     | −    | −    | −    | +    | +    | +    | +    |
| Amino acid transport system components|      |      |      |      |      |      |      |
| Permease                              | −    | +    | +    | +    | −    | −    | −    |
| ATP binding                           | +    | +    | +    | +    | −    | −    | −    |
| Substrate binding                     | −    | −    | −    | +    | +    | +    | +    |
| Fe(III) transport system components   |      |      |      |      |      |      |      |
| Permease                              | +    | +    | +    | +    | −    | −    | −    |
| ATP binding                           | −    | −    | −    | −    | +    | +    | +    |
| Substrate binding                     | −    | −    | −    | −    | −    | −    | −    |

H.s., Halobacterium sp. strain NRC-1; H.v., Haloferax volcanii; H.m., Haloarcula marismortui; H.w. Haloquadratum walsbyi; H.l., Halorubrum lacusprofundi; N.p, Natronomonas pharaonis; Natrialba magadii; (+) present; (−) absent.

changes by microarray analysis and mutant constructions, Kaur et al. (2006) [22] elucidated a systemic overview to metal stress response, thus providing a snapshot of various mechanisms involved in stress management. A total of 623 genes were found to be differentially regulated in presence of any of the six transition metals used for the study. Around 69% of these genes were early response genes; that is, they exhibited deviation from normal transcript levels within 0–25 minutes of metal exposure. However, 91% of these early response genes transcript levels reverted to preperturbation levels within 25–40 minutes. These included transcriptional regulator genes, transporter genes for phosphate, metals, and peptides, ribosomal protein genes, and protein export genes. Therefore, once the various damaged transcripts and proteins were replaced with the new proteins for managing metal stress and acclimatizing the cells to the new environment, the early response genes were found to revert to preperturbation levels [22].

Few of the early response genes found to be differentially regulated were transcriptional regulators like tfB and SirR. TfbB is the transcription initiation factor IIB. Its upregulation indicates a global response towards stress by increasing the rate of transcription to increase protein turnover. Similarly, the upregulation of SirR (silent information regulator) repressed the active uptake of Mn(II), thus providing the organism the ability to overcome the stress. Similar upregulation has also been observed in certain bacteria and yeast [167, 168]. Staphylococcus aureus and Staphylococcus epidermidis were shown to carry several copies of sirR genes that act as divalent metal cation-dependent transcriptional repressor [169]. cbiN, cbiM, and cbiQ involved in cobalt transport and dehydrogenases, and antioxidants like glutathione (GSH) [164]. Therefore, it follows that the genes involved in oxidative stress management are differentially regulated early in the stress management. Model haloarchaeal genomes, including Halobacterium salinarum and Haloferax volcanii, have been annotated with SOD [165] and catalase-peroxidase (KatG) genes [166]. Metal-induced ROS results in an early increase in the levels of transcripts of genes related to oxidative stress management like dehydrogenases and peroxidases in Halobacterium sp. strain NRC-1 [22].
zurM, zurA, and ycdH that encode Mn/Fe ABC-transporters were predicted to be putatively regulated by sirR in Halobacterium sp. strain NRC-1 [170]. This was found to be consistent with the observation that sirR is essential for survival during metal-induced stress. This was evident from the upregulation of Mn(II) uptake genes zurM, zurA, and ycdH in ΔsirR strain as compared to parent strain in Halobacterium sp. strain NRC-1. Thus, in the haloarchaeon Halobacterium sp. strain NRC-1, sirR acts as a Mn(II)-dependent autorepressor [22].

A putative Lrp (leucine-responsive regulatory protein) family protein VNG1197C was reported to upregulate the Cu(II)-P1B type ATPases gene yvgX in Halobacterium sp. strain NRC-1 [22]. VNG1197C was found to be a Cu(II)-dependent transcriptional activator carrying a metal-binding TRASH (trafficking, resistance, and sensing of heavy metals) domain. Kaur et al. (2006) [22] proposed that putative metallochaperones VNG0702H and/or VNG2581H deliver Cu(II)/Zn(II) to the TRASH domain of VNG1197C. This binding activates the transcription of yvgX as well as the metallochaperones, thus providing Cu(II) resistance to Halobacterium sp. strain NRC-1. A similar pattern involving a metallochaperone (CopM), a transcriptional regulator with C-terminal TRASH domain (CopT), and a P-type Cu(II) exporting ATPase (CopA) forming the cop gene cluster for Cu(II) resistance has been described in Sulfolobus solfataricus, a thermoacidophilic crenarchaeon [113, 114].

Thus, organisms have the ability to differentiate between metal ions and therefore elicit responses that enable better survival. These responses could be local or global but in effect would be to efficiently handle the stress. The transcriptional regulation exhibited by Halobacterium sp. strain NRC-1 is an example of how metal homeostasis is maintained.Transient changes in transcripts to resist metals may play a major role in haloarchaea.

4. Conclusion

Haloarchaea encounter metals in their natural environment and utilize some of these metals for various key physiological functions. However, at higher concentrations, these metals can be toxic, and thus haloarchaea exhibit metal resistance mechanisms. Knowledge about metal physiology in haloarchaea is cursory, and therefore global studies for gaining insights into the metabolic regulations in response to metal stress are required. Metal physiology studies in model haloarchaeon Halobacterium sp. strain NRC-1 show that they have the ability to elicit a tailor-made response to metal stress. Other genera of the halophilic Euryarchaeota have not yet been subjected to such detailed studies with regard to metal homeostasis and resistance. The development of standard molecular and genetic tools for haloarchaea may facilitate better understanding of the various components
involved in metal resistance including detoxifying enzymes, metallochaperones, and metal chelators and transporters. While assessing metal resistance in haloarchaea, the metal speciation should be given importance, as the metal might be unavailable to the cell for uptake, thus giving a higher MIC value. Therefore, beside understanding the molecular mechanisms underlying the resistance to metals, metal speciation and bio-availability studies should be carried out to obtain a complete picture. Further, this could facilitate the use of haloarchaea for bioremediation of metal-polluted hypersaline environments.

Acknowledgments

The authors thank the Ministry of Earth Science (MoES) and the Government of India for their funding of the project MoES/II-MRDF/I/38/P/10-PC-III.

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