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Metagenomic Profiling of Soil Microbes to Mine Salt Stress Tolerance Genes

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Osmotolerance is one of the critical factors for successful survival and colonization of microbes in saline environments. Nonetheless, information about these osmotolerance mechanisms is still inadequate. Exploration of the saline soil microbiome for its community structure and novel genetic elements is likely to provide information on the mechanisms involved in osmoadaptation. The present study explores the saline soil microbiome for its native structure and novel genetic elements involved in osmoadaptation. 16S rRNA gene sequence analysis has indicated the dominance of halophilic/halotolerant phylotypes affiliated to Proteobacteria, Actinobacteria, Gemmatimonadetes, Bacteroidetes, Firmicutes, and Acidobacteria. A functional metagenomics approach led to the identification of osmotolerant clones SSR1, SSR4, SSR6, SSR2 harboring BCAA_ABCtp, GSDH, STK_PknB, and duf3445 genes. Furthermore, transposon mutagenesis, genetic, physiological and functional studies in close association has confirmed the role of these genes in osmotolerance. Enhancement in host osmotolerance possibly though the cytosolic accumulation of amino acids, reducing equivalents and osmolytes involving BCAA-ABCtp, GSDH, and STKc_PknB. Decoding of the genetic elements prevalent within these microbes can be exploited either as such for ameliorating soils or their genetically modified forms can assist crops to resist and survive in saline environment.

Keywords: metagenome, halotolerance, SSU rRNA, soil microbiome, soil ecology

INTRODUCTION

Soil is a rich and dynamic ecosystem, containing a vast number of microorganisms (van Veen et al., 1997). Geological activities like weathering of rocks, winds and poor agricultural practice are continuously increasing salt contents of the soils (Jiang et al., 2007; Canfora et al., 2014). Enhanced soil salinity modulates the microbial community structure and its physiological activity (Jiang et al., 2007; Canfora et al., 2014; Shrivastava and Kumar, 2015). The majority of microbes surviving in salt stress conditions demonstrate osmotic tolerance for varying duration, which may extend even to their entire lifespan (Roberts, 2005). The salt stress tolerance mechanisms are complex phenomena where pathways are coordinately linked (Culligan et al., 2012). These metabolic strengths to mitigate osmotic stress, seem to be genetically evolved through horizontal gene transfer (Koonin and Wolf, 2012; Yan et al., 2015; Gupta et al., 2017). Description of these osmotic stress mechanisms is crucial for comprehensive understanding of the biology of saline soil microbes, and exploiting them for their applications in improving soil quality and crop yields (Xiao and Roberts, 2010; Zhengbin et al., 2011; Culligan et al., 2012, 2013, 2014; Fernandes, 2014).

A variety
of culture dependent studies have been carried out to decode the gene(s) involved in osmotolerance within halophilic or halotolerant microbes (Zuleta et al., 2003; Klähn et al., 2009; Naughton et al., 2009; Meena et al., 2017). These studies have deciphered the role of proteins, Na+\text/H+ pumps, compatible solutes in salt stress tolerance (Sakamoto and Murata, 2002; Roberts, 2005). However, culture independent approach provides a vast opportunity for searching salt tolerant gene(s) (Singh J. et al., 2009; Mirete et al., 2015; Kumar J. et al., 2016; Chauhan et al., 2017; Gupta et al., 2017). Only a few studies have used metagenomic approach to decode the microbial salt stress tolerance mechanisms from various environments like pond water (Kapardar et al., 2010a,b), brines and moderate-salinity rhizosphere (Mirete et al., 2015), human gut microbiome (Culligan et al., 2012, 2013, 2014). Incidentally, the number of genes/pathways identified for salt stress tolerance are far below than the number of microbes which have been identified to reside within these environments (Humbert et al., 2009; Mirete et al., 2015). Hereby, the current study was proposed to identify the genetic machinery used by microbes as survival strategies in salt stress condition using functional metagenomic approach. The current study led to the identification of a number of osmotolerant genes that could be used to develop strategies to ensure survival of microbes under saline conditions.

**MATERIALS AND METHODS**

**Saline Soil Sample Collection and Metagenomic DNA Isolation**

Saline soil samples were collected in sterile containers after carefully removing the surface layer (up to 10 cm) from Village Malab, District Nuh situated at 28.0107° N, 77.0564° E. Metagenomic DNA was extracted from 5 g of the soil sample (Supplementary Methods).

**Bacterial Strains and Growth Conditions**

Bacterial strains and plasmids used in the study are listed in Table 1. The oligonucleotides used in the study (GeNoRime, Shrimpex Biotech services Pvt. Ltd. India) are listed in Supplementary Table S1. *Escherichia coli* (DH10B) and *E. coli* (MKH13) strains were cultured in Luria-Bertani (LB) medium. Further, *E. coli* (DH10B) and *E. coli* (MKH13) strains containing pUC19 vector were cultured in LB medium supplemented with ampicillin (100 μg ml\(^{-1}\)) and NaCl [5.8% (w/v)]. The 5.8% of NaCl (w/w) is a lethal concentration for *E. coli* DH10B cells and will allow the growth of only osmotolerant clones. RFLP analysis of salt stress tolerant clones was performed after digesting their recombinant plasmid DNA with EcoRI & HindIII at 37°C for 12 h. The minimum inhibitory concentration assay and growth inhibition studies were performed to analyze the salt stress tolerance property (Kapardar et al., 2010a,b). Growth inhibition assays of salt sensitive *E. coli* MKH13 clones were performed with 3% NaCl (w/v) & 3.7% KCl (w/v), while 5.8% NaCl (w/v) & 5.5 % of KCl (w/v) were used for *E. coli* DH10B clones. Graphs (created using Origin61) are presented as the average of triplicate experiments, with error bars being representative of the standard error of the mean.

**Phylogenetic Reconstruction of Saline Soil Metagenome**

Saline soil metagenomic DNA was used to amplify the SSU rRNA gene (Supplementary Methods). The amplified product was used for next generation sequencing (NGS) with the aid of Roche 454 GS FLX+ platform (Morowitz et al., 2011; Gupta et al., 2017). Finally, Quantitative Insights Into Microbial Ecology (QIIME) 1.9.0 pipeline was implemented for SSU rRNA sequence data analysis (Caporaso et al., 2011). SSU rRNA gene sequence data was curated for quality, length and ambiguous bases as a quality filtering step. Each sample was pre-processed to remove sequences with length less than 200 nucleotides and more than 1,000 nucleotides and sequences with minimum average quality <25. Reads with ambiguities and barcode mismatch were discarded. Reads were assigned to operational taxonomic units (OTUs) using a closed reference OTU picking protocol using QIIME. The uclust was applied to search sequences against a subset of the Greengenes database, version 13_8 filtered at 97% sequence identity. The OTUs were classified taxonomically by using the Greengenes reference database at various taxonomic ranks (phylum, class, order, family, genus, and species).

**Metagenomic Library Screening and Characterization of Salt Resistant Clones**

Plasmid borne saline soil metagenomic library was prepared in *E. coli* DH10B using pUC19 vector (Supplementary Methods) (Chauhan et al., 2009, 2017) and manually screened for salt stress tolerant clones (Kapardar et al., 2010a,b). Salt stress resistant clones were screened by plating the soil metagenomic library (∼165,000 clones with an average insert of 1.89 Kb) on LB agar medium supplemented with ampicillin (100 μg ml\(^{-1}\)) and NaCl [5.8% (w/v)]. The 5.8% of NaCl (w/w) is a lethal concentration for *E. coli* DH10B cells and will allow the growth of only osmotolerant clones. RFLP analysis of salt stress tolerant clones was performed after digesting their recombinant plasmid DNA with EcoRI & HindIII at 37°C for 12 h. The minimum inhibitory concentration assay and growth inhibition studies were performed to analyze the salt stress tolerance property (Kapardar et al., 2010a,b). Growth inhibition assays of salt sensitive *E. coli* MKH13 clones were performed with 3% NaCl (w/v) & 3.7% KCl (w/v), while 5.8% NaCl (w/v) & 5.5 % of KCl (w/v) were used for *E. coli* DH10B clones. Graphs (created using Origin61) are presented as the average of triplicate experiments, with error bars being representative of the standard error of the mean.

**Genetic and Physiological Characterization of Salt Tolerance Genes**

The plasmid insert from salt resistant recombinant clones were sequenced using Sanger sequencing chemistry with primer walking approach at Eurofins Genomics India Pvt. Ltd (Bangalore, India). Sequence assembly was performed with Seq-Man sequence assembly software Lasergene package, version 5.07 (DNA Star, USA). Putative open reading frame (ORF) was predicted using an ORF finder tool at NCBI (http://www.ncbi.nlm.nih.gov/orf/gorf/gorf.html) and checked for the database homology with Basic Local Alignment and Search Tool (BLAST) (http://www.ncbi.nlm.nih.gov/blast). Encoded protein sequences were analyzed for the presence of conserved domains (CDD) (Marchler-Bauer et al., 2014), topology prediction (HMMTOP) (Tusnády and Simon, 2001), phylogenetic analysis (MEGA7) (Kumar S. et al., 2016), and various physiological parameters (Tsirigos et al., 2015). Transposon mutagenesis of pSSR1, pSSR4, pSSR6, and pSSR21 was carried out with EZ-Tn5™<Kan-2> Insertion Kit (Epiconcept Biotechnologies) following manufacturer's instructions. Transposon mutants of pSSR1, pSSR4, pSSR6, and pSSR21 were screened for the salt
stress resistant and sensitive phenotypes to identify the active osmotolerant genomic regions within the cloned DNA fragment in pSSR1, pSSR4, pSSR6, and pSSR21. Salt tolerant active loci encoding putative BCAA_ABCTP, GSDH, STK_Pknb, and DUF3445 genes of pSSR1, pSSR4, pSSR6, and pSSR21 were subcloned in pUC19 vector (E. coli MKH13 host) using standard molecular cloning techniques. The growth studies of subclones were performed to analyze their salt stress maintenance property in the presence of salt stressors NaCl [3.0% (w/v)] and KCl [3.7% (w/v)]. All assays were performed in triplicates for calculation of standard deviation. A parametric *t*-test was used to calculate the *p*-value.

**Elemental Quantification of Na⁺ in Salt Tolerant Clones**

Elemental Quantification of intracellular Na⁺ in E. coli MKH13 carrying the empty vector (pUC19) and salt tolerant recombinant subclones (SSR1C1, SSR4C1, SSR6C1, SSR21C1) was measured with inductively coupled plasma spectroscopy-atomic emission spectroscopy (ICP-AES) analysis (Mirete et al., 2015) at SAIF, IIT Bombay, India. Results were expressed as mg of Na⁺ g⁻¹ dry weight of cells. A parametric *t*-test was used to calculate the *p*-value.

**Data Availability**

Sequence reads generate in present study has been deposited in the NCBI SRA under accession number SRS2727172.

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**RESULTS**

**Phylogenetic Reconstruction of Saline Soil Metagenome**

Physico-chemical properties of saline soil showed that the pH of soil was 9.0 ± 0.025, while its electrical conductivity (EC) was 6.5 ± 0.023. Elemental analysis of soil showed the excessive presence of salts, sodium (105 ppm), potassium (155 ppm), and lithium (188 ppm), confirming its moderate saline nature. A good quality (A260/280 > 1.8), high molecular weight (>23 Kb) metagenomic DNA was extracted from the saline soil sample. Saline soil metagenomic DNA was used to analyze its SSU rRNA gene sequences to decode its native microbiome structure. Clustering of SSU rRNA gene identified a total of 487 OTUs distributed across seven microbial phyla (Figure 1). Out of 487 OTUs, we observed 153 unique OTUs (Supplementary Table S2). The inferred phylogeny of the soil microbiome based upon 153 unique OTUs (Figure 1) was comparable to the taxonomic classifications against with greengenes database, with most of the diversity of the microbiome being attributed to phyla Proteobacteria. The phylogeny was visualized by iTOL (Letunic and Bork, 2016). The dominant microbial phyla were Proteobacteria, Actinobacteria, Gemmatimonadetes, Bacteroidetes, Firmicutes, and Acidobacteria (Figure 1). Among these phyla, the majority of sequences were affiliated to Proteobacteria (43.7%) having a representation of Alphaproteobacteria (38.9%), Betaproteobacteria (7%),
Deltaproteobacteria (10.7%), and Gammaproteobacteria (43.2%); followed by Actinobacteria (21.8%) showing presence of Acidimicrobiia (72.47%) and Nitriruptoria (18.8%); Bacteroidetes (18.1%) having a proportionate representation of Rhodothermi (51.9%), Flavobacteriia (25.96%), Cytophagia (19.3%), and Gemmatimonadetes (11.3%) with a percentage representation of Gemm-2 (60.17%), Gemm-4 (12.3%), Gemm-1 (3.5%). Simultaneously, a minor fraction of sequences was affiliated to Acidobacteria (2.5%), Firmicutes (2.1%), and Nitrospirae (0.6%) microbial groups within saline soil microbiome. The taxonomic classification of saline soil microbiome confirms that a majority of microbial taxa belongs to phylum Proteobacteria (Figure 1) (Supplementary Table S2).

Screening of Salt Stress Resistant Clones from Saline Soil Microbiome

A saline soil metagenomic library was constructed with a total representation of 312 MB of cloned soil microbiome DNA. Primary screening of a saline soil metagenomic library at 5.8% NaCl (w/v) led to the identification of 24 salt stress tolerant clones. However, RFLP analysis indicated the presence of only four unique recombinant plasmids, labeled as pSSR1, pSSR4, pSSR6, and pSSR21. Minimum inhibitory concentration analysis showed almost two fold higher salt stress tolerance of SSR1, SSR4, SSR6, and SSR21 clones in comparison to the control E. coli (DH10B) (Supplementary Figure S1). The SSR1, SSR4, SSR6, and SSR21 also showed a statistically significant ($P = 0.0009$, $P = 0.0003$, $P = 0.0014$, $P = 0.004$) growth advantage in the presence of NaCl [4.0% (w/v)] (Figure 2A) and KCl [5.5% (w/v)] ($P = 0.0045$, $P = 0.0008$, $P = 0.0486$, $P = 0.0022$) as compared to E. coli (DH10B) strain carrying empty plasmid vector (pUC19) (Figure 2B), whereas no significant growth difference was observed between SSR1, SSR4, SSR6, SSR21, and native host E. coli (DH10B) carrying pUC19 in the presence of LB broth only (Figure 2C). Simultaneously pSSR1, pSSR4, pSSR6, and pSSR21 successfully complemented salt stress tolerance property within salt sensitive E. coli (MKH13) strain and showed a statistically significant growth advantage in the presence of NaCl [3.0% (w/v)] ($P = 0.0007$, $P = 0.0002$, $P = 0.0003$, $P = 0.0001$) (Figure 3A) and KCl [3.7% (w/v)] ($P = 0.0003$, $P = 0.0008$, $P = 0.0003$, $P = 0.0023$) (Figure 3B), as compared to E. coli (MKH13) strain carrying empty plasmid vector (pUC19). At the same time, no significant growth difference was observed between E. coli (MKH13) strain harboring pSSR1, pSSR4, pSSR6, pSSR21 as compared to E. coli (MKH13) strain carrying empty plasmid vector in the presence of LB broth only (Figure 3C).
Genetic and Physiological Characterization of Salt Stress Tolerant Clones
Salt Tolerant Clone SSR1
Sequence assembly of pSSR1 resulted into a contig of 2,938 bp with a 66.87% G+C content. Cloned insert shared 76% homology with a halophilic proteobacterial lineage Haliangium ochraceum, indicating its plausible affiliation within proteobacterial clade. The gene prediction analysis indicated the presence of three complete and one truncated ORF, encoding proteins of 93, 114, 383, and 149aa respectively. Translated nucleotide sequences of these ORFs were subjected to BLASTP (maximum e-value cutoff of 1e-34) analysis to identify the homologous sequence in the database (Table 2). Transposon mutagenesis analysis confirmed functionally active locus for osmotolerance property encompassing ORF3 (positioned between 927 and 2,078 bp) (Figure 4). ORF3 encoded transmembrane protein shared homology with a transmembrane ABC transporter ATP-binding protein of Betaproteobacteria bacterium SG8_39 (74%) and branched-chain amino acid ABC transporter substrate-binding protein of Oceanibacterium hippocampi (71%). Pfam database search identified the presence of a periplasmic ligand-binding domain of the ABC (ATPase Binding Cassette) type active transport systems, known to be involved in the transport of three branched chain aliphatic amino acids (leucine, isoleucine and valine) (Davidson et al., 2008). STRING analysis also predicted ORF3 as part of an interactive periplasmic binding protein dependent transport system. Further, NsitePred web server identified strong nucleotide binding sites (ATP Binding site at Gly14 and ADP binding site at Gly12) within ORF3 encoded protein. This nucleotide binding site could be NBD, a common feature for ATP binding proteins, as predicted by its functional assignment. In consideration of physiological role and all structural features of ORF3 encoded protein, it is a type of ABC transporter ATP-binding protein involved in salt stress maintenance possibly through energy dependent interaction with ABC membrane transporters involved in the exchange of the solutes across membrane, thus labeled as putative branched chain amino acid (BCAA) ABC transporter gene (BCAA_ABCTP). The putative BCAA_ABCTP gene was subcloned (pSSR1C1) to confirm its osmotolerance property. Time dependent growth curve analysis of SSR1C1 harboring BCAA_ABCTP showed a significant growth advantage in the presence of NaCl [3.0% (w/v)] (P = 0.0006) (Figure 5A) and KCl [3.7% (w/v)] (P = 0.0005) (Figure 5B) as compared to salt sensitive E. coli mutant MKH13 carrying only the empty vector (pUC19), while no significant difference was observed on LB only (Figure 5C). The intracellular elemental analysis in the presence of ionic stressor NaCl [3.0% (w/v)] showed that SSR1C1 has effectively reduced intracellular sodium ion concentration (P = 0.0134) in comparison to E. coli mutant MKH13 (Figure 5D). A reduced intracellular sodium concentration within SSR1C1 could be seen as a result of its transporter property, as predicated through
## TABLE 2 | Open reading frames identified in recombinant plasmids of osmotolerant clones.

| ORF details (ORF number, location, frame, product size) | Database homolog (accession no.) | Organism | Identity (%) | Coverage (%) | e-value | Conserved domain |
|--------------------------------------------------------|----------------------------------|-----------|--------------|--------------|---------|------------------|
| *pSSR1* (2938bp 66.87%) | ORF1, 13–293* +1, 93 aa | ABC transporter ATP-binding protein (*LivF*) (WP_056712341) | Bosea sp. Leaf344 | 81 | 94 | 5e-51 | ATP-binding cassette transporter nucleotide-binding domain (PPK13786) |
| | ORF2, 305–649, +2, 114aa | Hypothetical Membrane protein (WP_037447688) | Skermanella stibirestens | 58 | 95 | 2e-43 | – |
| | ORF3, 927–2078, +2, 383aa | ABC transporter (KPHD7993) | Betaproteobacteria bacterium SG8_39 | 74 | 93 | 0.0 | Type I periplasmic ligand-binding domain of ABC (cd006342) |
| | ORF4, 2617–2168, –1, 149aa | Transcriptional regulator (QJX81021) | Magnetospirillum sp. 64–120 | 71 | 91 | 1e-76 | ROS/MUCR transcriptional regulator protein (pfam05443) |
| *pSSR4* (2945bp 63.63%) | ORF1, 21–644, +3, 207aa | Hypothetical protein AMJ56_20605 (KPK02757) | Anaerolineae bacterium SG8_19 | 64 | 99 | 1e-91 | Glucose/Sorbose dehydrogenase (GSDH) (pfam07995) |
| | | Glucose/sorbose dehydrogenase-like protein (WP_011340324) | Pelobacter carbinolicus | 54 | 98 | 6e-69 | – |
| | ORF2, 2161–638, –2, 507aa | Hypothetical protein (CUR52060) | Uncultured Crenarchaeote | 36 | 47 | 7e-47 | mcbC-like_oxidoreductase (cd02142) |
| | ORF3, 2312–2945, +2, 210aa | DUF262 domain-containing protein (WP_081445540) | Actinomyces odontolyticus | 26 | 30 | 0.010 | DUF4131 (pfam13567) |
| *pSSR6* (1456bp 65.659%) | ORF1, (108–1145), +3, 345aa | Serine/threonine-protein kinase (WP_082990042) | Woeseia oceani | 81 | 100 | 0.0 | Catalytic domain of bacterial Serine/Threonine kinases, PinB and similar proteins (cd14014) |
| | ORF2, (1121–1456), +2, 111aa | Serine/threonine phosphatase (WP_088616118) | Woeseia oceani | 90 | 85 | 2e-59 | PP2’Cc Supergroup (cd00143) |
| *pSSR21* (2352bp 69.98%) | ORF1, 913–2*, –3, 309aa | No Similarity | – | – | – | – |
| | ORF2, 912–1925, +3, 337aa | Hypothetical protein *A3R84_263.10* (CGG46007) | Candidatus Handelsman bacteria RIFCSFLOWO2_12_FULL_64_10 | 51 | 97 | 7e-113 | DUF3445 (pfam13972) |
| | ORF3, 2097–2351*, –2, 84aa | Plus assembly protein RHF (OFW28714) | Acidobacteria bacterium RIFCSFLOWO2_12_FULL_60_22 | 53 | 98 | 4e-20 | TPR_10 (pfam13374) |

*Indicates truncated ORF.
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FIGURE 4 | Transposon insertion map of pSSR1, pSSR4, pSSR6, and pSSR21. T indicates a transposon insertion site identified within transposon positive mutants (no effect on plasmid derived osmotolerance property) while ↑ indicate transposon insertion site identified within transposon negative mutants (loss of plasmid derived osmotolerance property).

FIGURE 5 | Physiological Characterization of BCAA_ABCTP, GSDH, STK_Pknb, and duf3445 for osmotolerance. Growth curve analysis of osmotolerant phenotype SSR1C1 (•), SSR4C1 (▲), SSR21C1 (▼), and E. coli (MKH13) host strain carrying empty plasmid vector (■) in (A) LB broth supplemented with 3% NaCl (w/v), (B) LB broth supplemented with 3.7 % KCl (w/v), and (C) LB only. Intracellular Na⁺ estimation in E. coli (MKH13) strain harboring pSSR1C1, pSSR4C1, pSSR6, and pSSR21C1 and E. coli (MKH13) host strain carrying empty plasmid vector (D).

Salt Tolerant Clone SSR4

The pSSR4 harbors a G+C rich (G+C% = 63.63) insert of 2,945 bp. The cloned sequence did not share any homology at the nucleotide level in existing database sequences. A total of three ORFs were predicted within the cloned insert, encoding proteins of 207, 507, and 210 amino acids respectively (Table 2). Transposon mutagenesis analysis identified the functionally active locus within the sequence region (235 bp), encompassing ORF1 (Figure 4). ORF1 encodes a cytosolic protein homologous to hypothetical protein of Anaerolineae bacterium SG8_19 and Glucose/sorbosone dehydrogenase-like protein of Pelobacter carbinolicus. A Pfam analysis of ORF1 encoded protein indicates it as a glucose/sorbosone dehydrogenase protein having conserved domains for the protein family GSDH. It indicates that the ORF1 possibly encodes a glucose/sorbosone dehydrogenase involved in salt stress tolerance, possibly through the cytosolic accumulation of reducing equivalents (NADPH and GSH). Predicted GSDH gene was amplified from pSSR4 and subcloned to validate its osmotolerance property. Time dependent growth curve assay of SSR4C1 showed a significant growth advantage NaCl [3.0% (w/v)] (P = 0.0004) (Figure 5A) and KCl [3.7 % (w/v)] (P = 0.0006) (Figure 5B) as compared to salt sensitive E. coli mutant MKH13 carrying the empty vector (pUC19), while no significant difference has been observed on LB only (Figure 5C). The growth pattern of SSR4C1 was similar to SSR4. It also confirmed that the salt tolerance property of salt tolerant clone pSSR4 was possibly due to GSDH gene encoding glucose/sorbosone dehydrogenase protein.

Salt Tolerant Clone SSR6

Sequence assembly of pSSR6 generated a G+C rich (65.66%) contig of 1,456 bp. The blastn analysis identified its low similarity to Betaproteobacteria GR16-43 genome sequences, indicating its affiliation from proteobacterial clade. The cloned sequence encodes only one complete ORF (ORF1), encoding a cytosolic protein of 345 amino acids with a G+C content of 65.79% (Table 2). Transposon mutagenesis analysis also confirmed the functionally active locus within ORF2 (Figure 4). Homologs of translated ORF2, corresponds to putative serine/threonine protein kinase of Woesia oceani and Mycobacterium smegmatis str. MC2 155. A Pfam database search of ORF2 encoded protein indicates it as a putative serine/threonine protein kinase having genetic characterization. The growth pattern of SSR1C1 was found similar to the native SSR1 that confirms that salt tolerance of salt tolerant clone SSR1 was due to SSR1C1 cloned insert encoding a branched chain amino acid (BCAA) ABC transporter protein.
conserved domains for the protein family STKc_PknB, i.e., the catalytic domain of bacterial Serine/Threonine kinases, PknB family. Ser/Thr protein kinase homologs were found to be involved in osmosensory signaling in microbes (Hatzios et al., 2013). These identified proteins were important for the survival and in stress responses (Donat et al., 2009). The intracellular elemental analysis in presence of the ionic stressor NaCl [3.0% (w/v)] showed that SSR6 effectively reduced intracellular sodium ion concentration ($P = 0.0200$) in comparison to *E. coli* MKH13 (Figure 5D). A reduced intracellular sodium concentration within SSR6C1 could be due to enhanced ion transporter activity under the influence of signals generated by putative STKc_PknB of pSSR6 under the osmotic stress.

**Salt Tolerant Clone SSR21**

The pSSR21 was found to have a G+C rich (69.98%) insert of 2352 bp. The blastn analysis identified its homology with an *Actinomyces* strain *Allokutzneria albata*. Gene prediction has indicated the presence of three ORFs in pSSR21, encoding proteins of 309, 337, and 84 amino acids respectively. Among three identified ORFs, only ORF2 was complete, while other two ORFs (ORF1 and 3) were truncated. Transposon mutagenesis analysis has identified the functionally active locus within ORF2 sequence region (1,220 and 1,330 bp). The database homologs of ORF2 corresponds to hypothetical protein A3F84_26310 of *Candidatus Handelsmanbacteria* bacterium (Table 2). The pfam analysis identified the presence of conserved domains in the protein family DUF3445, i.e., protein of unknown function (DUF3445). The G+C content of ORF2 was found to be 69.96% and the predicted functionally active region, ORF2 was subcloned. Time dependent growth curve assay of SSR21C1 showed a significant growth advantage NaCl [3.0% (w/v)] ($P = 0.0005$) (Figure 5A) and KCl [3.7% (w/v)] ($P = 0.0045$) (Figure 5B) as compared to salt sensitive *E. coli* mutant MKH13 carrying only the empty vector (pUC19), while no significant difference has been observed on LB only (Figure 5C). Elemental Quantification of intracellular Na$^+$ in *E. coli* MKH13 carrying the empty vector and salt tolerant recombinant subclones SSR21C1 clearly showed that the cloned gene insert (duf3445) within SSR21C1 has significantly reduced the concentration of intracellular Na$^+$ ion ($P = 0.0174$) (Figure 5D).

**DISCUSSION**

Metagenomics has the potential to advance our knowledge by studying the genetic components of uncultured microbes (Singh A. H. et al., 2009; Mirete et al., 2015; Chauhan et al., 2017; Yadav et al., 2017). **Looking at the perspectives of metagenomics**, it was used to explore soil microbiome for its composition and genetic/physiological mechanisms allowing successful adaptation of microbes in saline environments. Simultaneously, these genes could be utilized as potential candidate to develop ever demanding drought resistant transgenic crops (Zhengbin et al., 2011) or osmotolerant microbes for food processing (Fernandes, 2014) and waste water treatment applications (Xiao and Roberts, 2010). Metagenomic analysis based on SSU rRNA gene has identified dominance of **Proteobacteria**, **Actinobacteria**, **Bacteroidetes**, and **Gemmatimonadetes** in saline soil microbiome. These results are in parallel with the outcome of previous studies defining microbial community composition of saline soil environment (Zhang et al., 2003; Ma and Gong, 2013; Canfora et al., 2014; Kadam and Chuan, 2016). Canfora et al. has reported a correlation in abundance of a microbial group with respect to soil salinity. They had indicated a relative abundance of **Proteobacteria** with **Bacteroidetes** were positively and **Acidobacteria** was negatively correlated with salinity (Canfora et al., 2014). Similarly **Actinobacteria** was also been reported as another dominant microbial phylum in saline ecosystems (Kadam and Chuan, 2016). **Gemmatimonadetes** is another well-known hypersaline microbial phylum associated with biogeochemical transformations (Zhang et al., 2003). The existence of halophilic subcomponents within the identified microbial phylum, possibly making them capable to proliferate in a saline environment. These studies explain the abundance of **Proteobacteria**, **Actinobacteria**, **Gemmatimonadetes**, and **Bacteroidetes** in the studied ecosystem. Evolution of novel genetic features is a key to their successful survival in a changing environment (Gupta et al., 2017; Kumar Mondal et al., 2017). These saline microorganisms could have evolved salt stress tolerant genetic machinery to adapt and survive under salt induced osmotic stresses (Meena et al., 2017). A number of genetic elements were decoded for osmotolerance property from cultured and uncultured microbial representatives (Kapardar et al., 2010a,b; Culligan et al., 2012, 2013, 2014; Kim and Yu, 2012; Mirete et al., 2015). However, there is a disparity in a number of reported salt tolerance genes with a number of microorganisms from an ecosystem (Humbert et al., 2009; Mirete et al., 2015). This divergence could be allied with a number of factors like unculturability (Kim and Yu, 2012), lack of good quality genomic/metagenomic DNA (Kumar J. et al., 2016) and issues with foreign gene expression (Prakash and Taylor, 2012). An additional effort was made in the current study to decode osmotolerance genes prevalent in these saline soil microorganisms using functional metagenomics. It leads to the identification of four unique osmotolerant clones harboring DNA insert showing affiliation within halophile genomes. Genetic and physiological analysis has identified genes encoding putative proteins like membrane bound branched chain amino acid (BCAA) ABC transporter protein (BCAA_ABCTP), Glucose/sorbitosone dehydrogenase, cytosolic STKc_PknB and DUF protein are responsible for osmotolerance property within salt stress tolerant clones. Among these, the role of branched chain amino acid (BCAA) ABC transporter protein and glucose/sorbitosone dehydrogenase in osmotolerance are well documented (Takami et al., 2002; Brosnan and Brosnan, 2006), while the scanty information is available about role for STKc_PknB and DUF445 protein in stress maintenance (Hatzios et al., 2013). **ABC branched chain amino acid (BCAA) transporters** are widely distributed in various marine microbes like *Oceanibacillus iheyensis* (Takami et al., 2002), *Salinispora*, *Bacillus*, and *Roseobacter* strains (Penn and Jensen, 2012). BCAA_ABCTP proteins are involved in the transport of branched chain aliphatic amino acids such as leucine, isoleucine and valine at...
high salt concentration. In the presence of 2-oxoglutarate and pyridoxal-5-phosphate, these branched chain amino acids are further converted to L-glutamate by branched chain amino acid transferase (Hutson, 2001). Accumulated glutamate acts as an osmoprotectant upon hyper-osmotic shock and activates sets of genes that allow the host to achieve long-term adaptation to high osmolality (Gralla and Vargas, 2006). They also account for a significant proportion of the genes observed in the marine metagenome. Branched chain amino acid transporters are probably an important marine adaptation because accumulated glutamate may function as a counter ion for K⁺, which balances the electrical state of the cytoplasm (Penn and Jensen, 2012). Previous studies have reported a regulatory relationship between K⁺ and glutamate accumulation in response to osmotic stress in enteric bacteria and haloalkaliphilic archaea Natronococcus occultus (Kokoeva et al., 2002). Similarly, T. consotensis, a halotolerant bacterium accumulates glutamate to maintain electrical equilibrium within the cell in response to high salt concentrations (Rubiano-Labrador et al., 2015). This background information explains the possible physiological role of the BCAA_ABCTP gene of pSSR1 to increase host osmotolerance.

Glucose/Sorbosone dehydrogenase (GSDH) is responsible for the production of NADPH through oxidative cleavage of glucose (Oubrie et al., 1999). Under salt stress condition, NADPH acts as reducing potential for output of reduced glutathione (GSH) and involved in activity of membrane bound NADPH oxidase, which results in accumulation of hydrogen peroxide (H₂O₂) (Wang et al., 2008). H₂O₂ acts as a signal in regulating G6PDH activity and expression of this enzyme in the glutathione cycle through which the ability of GSH regeneration was increased under salt stress (Wang et al., 2008). Thus, G6PDH plays a critical role in maintaining cellular GSH levels under long-term salt stress conditions (Wang et al., 2008). It indicates that GSDH of pSSR4 is involved in salt stress tolerance possibly through the cytosolic accumulation of reducing equivalents (NADPH and GSH).

While in case of pSSR6 only one ORF was identified, sharing homology with Serine/Threonine kinases. This encoded protein also possesses two conserved domains for the protein family STKc_PknB, i.e. the catalytic domain of bacterial Serine/Threonine kinases, PknB and similar proteins; STKs and TOMM_kin_cyc, i.e., TOMM system kinase/cyclase fusion protein. STKs are well known for activating genetic locus concerned with osmosensing (Hatzios et al., 2013) and inducing topological changes such as DNA supercoiling (Gupta et al., 2014). These osmosensing signal and DNA supercoiling could initiate uptake of the osmolyte glycine betaine, proline (Csonka, 1989) or initiates the expression of genetic elements required to cope with osmotic stress (Higgins et al., 1988). This could be the possible mechanism by which putative STK_PknB of pSSR6 might be extending osmotolerance to the host E. coli.

The pSSR21 ORF2 encodes a protein sharing homology with a hypothetical protein of Candidatus Handelsmanbacteria possessing a conserved domain for DUF3445 superfamily, i.e., an uncharacterized protein family having conserved RLP sequence motif (Bateman et al., 2010). However, its physiological characterization and intracellular ion concentration analysis indicates that it extends host osmotolerance property by maintaining low intracellular ion concentration even in the presence of anionic stressor. However, a detailed mechanism still needs to be elucidated.

CONCLUSION

In this study, the functional metagenomic approach was used to decipher salt stress tolerant genes in the saline soil microbiome. Identification of salt tolerant genes BCAA_ABCtp, GSDH STK_Pknb, and daf3445 has enriched our understanding about the survivability and adaptability of microbes in the highly saline soil ecosystem. These salt tolerant genes can be used for crop improvement and for producing bioactive molecules under high salt conditions, which reduces the chances of contamination by other microbes.

AUTHOR CONTRIBUTIONS

NC, MV: Designed the project; MV, VA: Performed experiments and NGS sequencing; SG, VM, and VA: Performed data analyses; MV, VM, and NC: Wrote the manuscript. All authors have read and approve the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmicb.2018.00159/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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