A halotolerant aldose reductase from \textit{Debaryomyces nepalensis}: gene isolation, overexpression and biochemical characterization†

Bhaskar Paidimuddala, Gopala Krishna Aradhyaam and Sathyanarayana N. Gummadi \textsuperscript{a,*}

Aldose reductase (AR) catalyzes the conversion of aldoses to their corresponding polyols in yeasts and filamentous fungi. ARs have the potential to be exploited for the enzymatic production of xylitol, thus the identification and characterization of ARs from novel strains have gained interest. In this study, we chose the novel yeast \textit{Debaryomyces nepalensis} as a source for an AR gene. For the first time, here we isolated the AR gene from \textit{D. nepalensis} (DnAR) that encodes a protein of 320 amino acids with a predicted molecular weight of 36.7 kDa using the RACE technique. It was heterologously expressed in \textit{Escherichia coli} as a His-tagged fusion protein and purified. The enzyme showed strict NADPH dependence and broad substrate specificity with high catalytic efficiency for arabinose, xylose and 3-nitro benzaldehyde. Remarkably, it was active and stable in the presence of high concentrations of salts (KCl/NaCl), thus exhibiting halotolerance. It showed 75% and 45% activity at 0.5 and 1 M concentration of salts respectively. Enzyme half-lifetime at 1 M KCl and 1 M NaCl was found to be 30 h and 16.5 h respectively. Furthermore, to explore the structural basis of its halotolerance, we built a homology model of DnAR. Surprisingly, we found that the existence of a uniform negative electrostatic potential over the protein surface, which is one of the known mechanisms governing protein halotolerance. Therefore, DnAR could be exploited as a biocatalyst to develop an enzyme based bioprocess for xylitol production from lignocelluloses. Moreover, this is the first report providing the genetic sequence and biochemical characteristics of a halotolerant aldose reductase.

1. Introduction

Aldose reductase (AR) (EC 1.1.1.21) is a member of the aldo-keto reductase (AKR) super family of enzymes, which catalyzes the reduction of aldehydes to their corresponding alcohols.\textsuperscript{1,2} ARs are highly conserved and found in animals, plants and microbes.\textsuperscript{3} Though broad substrate specificity is the signature property of ARs, the exact biological function differs among the organisms.\textsuperscript{2,3} In animals and plants, AR preferably catalyzes the conversion of glucose to sorbitol with strict dependence on NADPH.\textsuperscript{4,5} AR in humans has been implicated in the onset of diabetic complications by forming excessive polyols in the hyperglycemic state in tissues.\textsuperscript{4} Due to this reason, numerous reports on the development of therapeutic AR inhibitors have been published.\textsuperscript{5,6} In contrast to human AR, the yeast AR is involved in the reduction of aldopentoses such as xylose, arabinose and erythrose with concomitant oxidation of either NADPH or NADH.\textsuperscript{7} Therefore, yeast ARs have the potential for the exploitation of lignocellulosic xylose to produce xylitol, a pentose alcohol.\textsuperscript{8,9}

Xylitol is a multi-beneficial natural sugar substitute with potential applications in sugar-free foods and drinks, oral hygiene, pharma and cosmetic products.\textsuperscript{10} Currently, xylitol production at industrial scale involves chemical hydrogenation of xylose extracted from lignocellulose under extreme conditions of pressure and temperature with toxic catalysts.\textsuperscript{11} Although microbial production of xylitol is advantageous as compared to chemical processes in terms of cost and environmental impact, catabolite repression and downstream processing from by-products (glycerol, arabilot and ethanol) makes it expensive.\textsuperscript{12} Since only one enzyme AR, requires for the production of xylitol, the development of enzymatic bioprocess could surpass the limitations of current processes.\textsuperscript{8,9} Therefore, ARs have gained interest, leading to the characterization of putative ARs and identification of new ARs having remarkable properties such as halotolerance and thermostolerance which help sustain industrial conditions as well as salts contaminated lignocellulose hydrolysates.
For this study, we chose *Debaryomyces nepalensis*NCYC 3413, a non-pathogenic saccharomyces yeast which was previously isolated from rotten apple.\(^{13}\) It has been shown to survive in a medium containing pectin as the sole source of carbon and can overcome osmotic stress by producing polyols.\(^{14}\) *D. nepalensis* could utilize both hexoses and pentoses, and xylitol was found to be a major product when grown in the medium containing xylose, suggesting the presence of aldose metabolizing enzymes.\(^{15}\) Nevertheless, earlier we purified a protein with xylose reductase activity from *D. nepalensis*, hence it has been proven as a good candidate strain to take for AR gene fishing.\(^{16}\) However, lack of information on its genome sequence was eliminating the possibilities of specific genes isolation and their cloning.

In the present study, we attempted AR gene isolation from *D. nepalensis* by designing the primers based on genome sequence of its close relatives such as *D. Hansenii* and *Candida* species. Later, the obtained partial AR gene sequence was taken to design the primers for the full-length gene isolation by rapid amplification of cDNA ends (RACE), so that we successfully isolated novel AR gene from *D. nepalensis* (DnAR). Next, it was overexpressed as a His-tagged fusion protein in *E. coli* Rosetta, purified and its biochemical properties were determined. The enzyme showed strict dependence on cosubstrate NADPH, broad substrate specificity and halotolerance. In addition, we developed a homology model for DnAR using SWISS MODEL automated mode. It was found that the TIM barrel [([beta]/alpha] barrel) fold, residues involving catalysis substrate binding and important residues mediating cosubstrate specificity are conserved in the model (Fig. 3).

2. Results

2.1. Molecular cloning of *D. nepalensis* AR gene

Using the primers F1 and R1, an amplicon of 0.85 kb size was obtained from *D. nepalensis* gDNA (Fig. 1A). Upon sequence alignment, it showed high homology with other aldose (xylose) reductase genes from various yeasts, which confirmed the successful isolation of partial DnAR gene. The incomplete ORF of DnAR (61–918 bp region of full-length gene) was used for designing gene-specific primers to amplify the missing terminals by RACE. The complete ORF of DnAR gene (963 bp) was determined by overlapping of the resultant sequences of PCR products from 5’ RACE (0.63 kb) and 3’ RACE (0.84 kb) (Fig. 1B).

Using the primers F2 and R2 designed based on the RACE results, the full-length DnAR gene was amplified from cDNA as well as from gDNA (Fig. 1C).

The DnAR gene amplified from both gDNA and cDNA was sequenced and its deduced amino acid sequence is shown in Fig. 2. The sequence results revealed that the gene was uninterrupted by introns. DnAR showed 70% sequence similarity with aldose (xylose) reductase from *C. tenuis* (CXR) hence the coordinates of *CXR* crystal structure (PDB ID: 1K8C) was used as template to create the homology model of DnAR using SWISS MODEL automated mode. It was found that the TIM barrel [([beta]/alpha] barrel) fold, residues involving catalysis substrate binding and important residues mediating cosubstrate specificity are conserved in the model (Fig. 3).

2.2. Heterologous expression and purification

The plasmid pET28a-DnAR encoding N-terminal His6-tagged DnAR was expressed in *E. coli* Rosetta under IPTG induction. The overexpressed protein constitutes 60% of the total cellular protein.
soluble protein. The cell-free lysate soluble fraction showed AR activity when xylose and NADPH were used as substrate and cosubstrate respectively, confirming the successful heterologous expression of DnAR. Next, the resultant recombinant protein was purified in a single step with an immobilized metal ion affinity chromatography (IMAC) purification using Ni²⁺ chelating column. The molecular weight of purified DnAR (with tag) was ~38.7 kDa, which is consistent with its predicted molecular weight (Fig. 4).

The activity yield obtained by this purification strategy was found to be 51% (3.3 U mg⁻¹) (Table 1). To confirm if the overexpressed protein is AR or not, the purified protein was trypsin digested and subjected to LC-MS/MS analysis. The digested peptide fragments of DnAR matched with parts of protein sequences of ARs from different organisms (Fig. S1†). Moreover, the differences in residues between the previously characterized native xylose reductase and present recombinant DnAR confirmed that this DnAR is one of the isomeric forms of AR from D. nepalensis.

2.3. Effect of pH, temperature and metal ions on DnAR activity

The effect of pH on DnAR activity was studied by measuring the activity at various pHs ranging between 4.0 and 10.0 by keeping temperature as constant. Maximum specific activity of 80 ± 2 U mg⁻¹ was obtained at pH 7.0 and the enzyme demonstrated

<table>
<thead>
<tr>
<th>Step</th>
<th>Total protein (mg)</th>
<th>Total activity (U)</th>
<th>Specific activity (U mg⁻¹)</th>
<th>Purification fold</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude</td>
<td>51.3</td>
<td>26</td>
<td>0.5</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Purified</td>
<td>4.0</td>
<td>13.3</td>
<td>3.3</td>
<td>6.6</td>
<td>51.2</td>
</tr>
</tbody>
</table>

The activity yield obtained by this purification strategy was found to be 51% (3.3 U mg⁻¹) (Table 1). To confirm if the overexpressed protein is AR or not, the purified protein was trypsin digested and subjected to LC-MS/MS analysis. The digested peptide fragments of DnAR matched with parts of protein sequences of ARs from different organisms (Fig. S1†). Moreover, the differences in residues between the previously characterized native xylose reductase and present recombinant DnAR confirmed that this DnAR is one of the isomeric forms of AR from D. nepalensis.
activity in a broad pH range by retaining 60% activity at pH 6.0 and 55% activity at 8.0. At pH 5.0 and 9.0 only 30% of the maximum activity was observed (Fig. 5A). The enzyme activity increased from 10 to 45 °C; maximum activity was shown at 45 °C and beyond 50 °C a drastic drop in enzyme activity was observed (Fig. 5B).

The effect of metal ions on DnAR activity was studied at three different concentrations (0.5, 1.0 and 2.0 mM) of various metal ions. Ca$^{2+}$ and Mn$^{2+}$ up to 2 mM concentration did not significantly affect the activity (75% of residual activity), whereas 0.5 mM Cu$^{2+}$ completely inhibited the enzyme activity (Fig. 5C). Fe$^{2+}$ and Ni$^{2+}$ showed 50% reduction in activity at 2 mM whereas 80% reduction in activity was observed when 2 mM Mg$^{2+}$ was used in the reaction mixture. In the presence of Zn$^{2+}$, DnAR activity was reduced to 60% of its original activity at 0.5 mM and did not show further reduction at higher concentrations of Zn$^{2+}$ (Fig. 5C).

### 2.4. Cosubstrate and substrate specificity

Cosubstrate specificity was tested by measuring the enzymatic activity in the presence of different concentrations ranging from 0 to 1 mM NADH and NADPH, and the results clearly showed that DnAR is specific only for NADPH. Further, the kinetic properties of the enzyme for cosubstrate were determined by performing kinetics as described in materials and methods. $K_M$ for NADPH was found to be $0.13 \pm 0.01$ mM and $k_{cat}/K_M$ was $728 \pm 12$ s$^{-1}$ mM$^{-1}$. The DnAR showed broad substrate specificity, which is a key property of the enzymes belonging to the AKR family (Table 2). Xylose, arabinose, ribose, galactose, glucose, fructose and mannose were tested as substrates for DnAR with NADPH as a cofactor. Among the tested, xylose ($K_M = 106 \pm 12$ mM) and arabinose ($K_M = 110 \pm 3$ mM) showed higher affinity to the enzyme. However, DnAR showed higher $k_{cat}$ for arabinose ($163 \pm 1$ s$^{-1}$) when compared to xylose ($108 \pm 3$ s$^{-1}$). It was also found that the catalytic efficiency ($k_{cat}/K_M$) for arabinose is 46% higher than that for xylose. Moreover, DnAR was also reduced another pentose ribose and hexoses such as glucose, galactose and fructose (Table 2). But DnAR did not show any activity towards mannose (data not shown). Among the non-sugar carbonyl substrates tested for activity, the enzyme showed higher catalytic efficiency with 3-nitro benzaldehyde and a lower with glyoxal (Table 2).

### Table 2 Substrate specificity of DnAR. The kinetic parameters were determined by non-linear regression. The represented values are means of three analytical replicates with ± SD. $K_M$: Michaelis–Menten constant, $k_{cat}$: turnover number. $k_{cat}/K_M$: catalytic efficiency

<table>
<thead>
<tr>
<th>Substrate</th>
<th>$K_M$ (mM)</th>
<th>$k_{cat}$ (s$^{-1}$)</th>
<th>$k_{cat}/K_M$ (mM$^{-1}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xylose</td>
<td>106 ± 12</td>
<td>108 ± 4</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>Arabinose</td>
<td>110 ± 3.0</td>
<td>163 ± 1</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Ribose</td>
<td>377 ± 21</td>
<td>92 ± 3</td>
<td>0.24 ± 0.1</td>
</tr>
<tr>
<td>Galactose</td>
<td>572 ± 82</td>
<td>106 ± 9</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Glucose</td>
<td>889 ± 75</td>
<td>61 ± 2</td>
<td>0.07 ± 0.0</td>
</tr>
<tr>
<td>Fructose</td>
<td>1269 ± 231</td>
<td>11 ± 1</td>
<td>0.01 ± 0.0</td>
</tr>
<tr>
<td>Glyoxal</td>
<td>70 ± 2.0</td>
<td>41 ± 1</td>
<td>0.58 ± 0.5</td>
</tr>
<tr>
<td>Isophthaldehyde</td>
<td>2.0 ± 0.2</td>
<td>28 ± 0.5</td>
<td>12.0 ± 2.3</td>
</tr>
<tr>
<td>Benzaldehyde</td>
<td>3.3 ± 0.4</td>
<td>11 ± 0.5</td>
<td>3.3 ± 1.2</td>
</tr>
<tr>
<td>Pyridine 3-carboxylddehyde</td>
<td>4.5 ± 0.5</td>
<td>7 ± 0.5</td>
<td>1.6 ± 1.0</td>
</tr>
<tr>
<td>3-Nitro benzaldehyde</td>
<td>1.7 ± 0.4</td>
<td>40 ± 0.5</td>
<td>24 ± 1.2</td>
</tr>
</tbody>
</table>

### Table 3 Xylose kinetics of DnAR in the presence of salts. The kinetic parameters were determined by non-linear regression. The represented values are means of three analytical replicates with ± SD. $K_M$: Michaelis–Menten constant, $k_{cat}$: turnover number. $k_{cat}/K_M$: catalytic efficiency

<table>
<thead>
<tr>
<th>Salt</th>
<th>$K_M$ (mM)</th>
<th>$k_{cat}$ (s$^{-1}$)</th>
<th>$k_{cat}/K_M$ (mM$^{-1}$ s$^{-1}$)</th>
<th>% catalytic efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>106 ± 12</td>
<td>108 ± 4</td>
<td>1.03 ± 0.3</td>
<td>100</td>
</tr>
<tr>
<td>0.5 M KCl</td>
<td>171 ± 10</td>
<td>133 ± 3</td>
<td>0.78 ± 0.3</td>
<td>76</td>
</tr>
<tr>
<td>0.5 M NaCl</td>
<td>149 ± 16</td>
<td>112 ± 5</td>
<td>0.75 ± 0.3</td>
<td>73</td>
</tr>
<tr>
<td>1.0 M KCl</td>
<td>227 ± 23</td>
<td>86 ± 5</td>
<td>0.38 ± 0.2</td>
<td>37</td>
</tr>
<tr>
<td>1.0 M NaCl</td>
<td>200 ± 30</td>
<td>60 ± 3</td>
<td>0.30 ± 0.1</td>
<td>29</td>
</tr>
</tbody>
</table>
2.5. Halotolerance of DnAR

The recombinant DnAR activity was determined in the presence of various concentrations of NaCl and KCl ranging between 0 and 2 M at optimal pH 7.0 and optimal temperature 45 °C (Fig. 6A). The enzyme exhibited specific activity 110 ± 3 U mg⁻¹ (75% of original activity) and 65 ± 2 U mg⁻¹ (45% of original activity) at 0.5 and 1 M KCl respectively. However, in the presence of 0.5 M and 1 M concentration of both salts respectively (Table 3). The stability of the enzyme was studied in the presence of 1 M and 2 M NaCl and KCl at 30 °C. The residual activity at various time points was

![Fig. 7 Surface electrostatic potentials of halotolerant DnAR and aldose (xylose) reductase from non-halotolerant C. tenuis (PDB ID: 1K8C). The first, second, third and fourth row were seen from the right, left, front and back of the structures, respectively. The red surface was corresponded to negatively charged residues and the blue surface corresponded to positively charged residues. The potentials were contoured to −1.0 kT per electron (red) and +1.0 kT per electron (blue).](image)

![Fig. 8 Far-UV CD spectra of DnAR in the presence of salts. (A) CD spectra of DnAR in the presence of 0–2 M KCl (B) CD spectra of DnAR in the presence of 0–2 M NaCl. The CD spectra were measured using a protein concentration of 3 μM in 10 mM sodium phosphate buffer (pH 7.0) at ambient temperature. The CD signals at low wavelengths (<205 nm) were obstructed by high concentration of salt (not shown in the figure). The experiment was performed in three analytical replicates and mean values were taken for representation.](image)
measured and the data were fitted to the first-order deactivation kinetics and the half-life of enzyme was determined. DnAR exhibited half-life time of 30 ± 2 h in the absence of salts (control). In the presence of 1 M KCl, no change in the half-life time was observed when compared to the control, whereas the half-life was reduced to 16.5 ± 3 h in the presence of 1 M NaCl (Fig. 6B). It was found that NaCl affected both the activity and the stability of the enzyme more than KCl at all concentrations. Moreover, the surface electrostatic properties of DnAR when compared to non-halotolerant aldose (xylose) reductase from C. tenuis revealed the presence of more negative surface electrostatic potential over the surface of DnAR than the CtxR (Fig. 7).

2.6. Circular dichroism studies

The secondary structural elements of DnAR were analyzed in the presence of 0–2 M concentrations of salts (NaCl/KCl) by far-UV CD spectroscopy. At low wavelengths (<205) high salt concentration in the samples obstructed the CD signals. However, the larger ellipticity of the two negative peaks was observed at 208 nm and 222 nm, which corresponded to α-helix. In the presence of 2 M NaCl and KCl, no major changes in the secondary structure of the protein were observed with respect to control (Fig. 8A and B). The effect of salts on the thermal unfolding of DnAR was investigated in the presence of salts up to 2 M. As shown in Fig. 9, the thermal melting curves in the presence of salts showed a decrease in Tm of protein by 8 °C and 10 °C in the presence of KCl and NaCl respectively as compared to the control (Fig. 9A–C). In spite of that, we observed 3 °C difference in Tm between 1 M and 2 M of KCl (Fig. 9B) whereas no significant changes in Tm were observed between 1 M and 2 M NaCl (Fig. 9C).

3. Discussion

Microbial or enzymatic conversion of cellulosic and lignocellulosic biomass to ethanol, xylitol and other industrially important products is prominent in the research field of bioenergy and biorefinery. One of the major problems in this field is the utilization of both hexoses and pentoses, and various efforts have been made to engineer the existing strains and in screening novel organisms capable of utilizing both hexoses and pentoses. We previously isolated halotolerant yeast D. nepalensis from rotten apple, which is capable of utilizing both hexoses and pentoses and tolerate both NaCl and KCl at 2 M. The strain was capable of converting xylose to xylitol with a yield of 0.6 g g⁻¹, which intrigued to isolate the enzyme responsible for xylitol production from this strain.

The aldose reductase gene isolated from D. nepalensis NCYC 3413 has a length of 963 bp and encodes a protein containing 320 amino acids. DnAR exists as a dimer with each monomeric subunit of 36.7 kDa. The size of the monomeric subunit of DnAR is matching with ARs from other organisms where it ranges from 35 to 40 kDa. The DnAR has a conserved TIM barrel fold, a structural property of the enzymes belonging to the AKR super family (Fig. 3). It shares other common features of this family of enzymes such as dependence on nicotinamide cofactors, hydrophobic substrate binding pocket and broad substrate specificity. The multiple sequence alignment of DnAR protein sequence with reported aldose (xylose) reductases showed conservation of residues those involving in catalysis, substrate and cosubstrate binding (Fig. S1†).

The DnAR gene was overexpressed in E. coli Rosetta and final yield of the purified DnAR obtained by the single-step affinity chromatography was 48 mg g⁻¹ dry weight of E. coli (Table 1). DnAR showed strict NADPH specificity as a signature property of ARs which distinct it from typical xylose reductases which are specific to either NADPH or NADH. DnAR exhibited broad substrate specificity like other AKR proteins. Similar to AR from C. boidinii the catalytic efficiency of DnAR with arabinose was higher than xylose. It is another feature that separate it from typical xylose reductases (usually XRs are highly specific to xylose). Contrastingly, AR from C. tenuis showed maximum catalytic efficiency with α-erythrose. DnAR was also reduced hexoses namely glucose and fructose to a certain extent (Table 2). Nevertheless, toxic non-sugar substrates were also reduced to a significant extent by the enzyme similar to other ARs (Table 2).

The activity of enzymes can be influenced by the presence of metal ions, so in this study we tested several divalent metal ions for the activity of DnAR. We found that the DnAR exhibited
moderate tolerance towards most of the metal ions (Fig. 5C). Nevertheless, the observed tolerance was higher than the *C. tropicalis* aldose (xylose) reductase which was known to be a highly active enzyme ($k_{cat}/K_M = 7.62 \text{ s}^{-1} \text{ mM}^{-1}$).23 Conversely, DnAR was susceptible to Cu²⁺ toxicity as like enzymes from *C. tropicalis* and *C. parapsilosis*.24,25 Cu²⁺ is known to exert its effect by induction of site specific oxidation in human aldose reductase25 and probably the same mechanism might be applicable for DnAR.

The halophilic enzymes require salt to show optimal activity whereas halotolerant enzymes do not require salts for optimal activity.26 Similar to other halotolerant enzymes, DnAR showed optimal activity in the absence of salt and its activity decreased gradually upon increasing salt concentrations up to 2 M. In the presence of 0.5 M KCl and 0.5 M NaCl, DnAR exhibited retention of 76% and 73% of catalytic efficiency respectively at 45 °C. However, it showed only 37% and 29% retention of catalytic efficiency in the presence of 1 M KCl and NaCl respectively (Table 3). The reduction in activity can be probably attributed to the prevention of coenzyme release from the cofactor binding pocket of the enzyme in the presence of salts as indicated by a decrease in $k_{cat}/K_M$ values for xylose (Table 3). Nevertheless, DnAR exhibited remarkable salt stability as shown in Fig. 6. The half-life of the enzyme in 1 M KCl was found to be 30 ± 2 h (same as control) and 16 ± 3 h in the presence of 1 M NaCl at 30 °C (Fig. 6B). The effect of NaCl was larger than that with KCl, which is similar to the other halotolerant proteins.27,28 *C. tropicalis* xylose reductase (having high catalytic efficiency) was highly unstable in the presence of salts. Even at low salt concentrations (0.1 mM NaCl), the activity of *C. tropicalis* enzyme was reduced to 25% upon incubation for 1 h.29 The effect of NaCl on the activity and stability of DnAR was greater than with KCl at all the tested concentrations. The CD spectra in the presence of salts suggested the existence of regular conformational stability up to 1 M NaCl.29 DnAR was found to be more susceptible to Cu²⁺ toxicity as like enzymes from *C. tropicalis* and *C. parapsilosis*.24,25 Cu²⁺ is known to exert its effect by induction of site specific oxidation in human aldose reductase25 and probably the same mechanism might be applicable for DnAR.

4. Conclusions

We isolated novel aldose reductase gene from the halotolerant yeast *D. nepalensis*, cloned, overexpressed and its biochemical properties were determined. To the best of our knowledge, DnAR showed peculiar property of halotolerance, high catalytic efficiency and broad substrate specificity. Based on our results, we suggest that this enzyme can be used as a potential biocatalyst for upcoming in vitro xyitol production from lignocellulose hydrolysates. Further mutational and crystallographic studies will give more insights into the structure and function relationship of DnAR.

5. Materials and methods

5.1. Materials

The strain *Debaryomyces nepalensis* NCYC 3413 was used as a source of AR gene. *E. coli* DH5α and *E. coli* Rosetta (both Novagen, USA) were used as cloning and host strains, respectively. The plasmid pGEM-T easy vector (Promega, Germany) was used as a cloning/sequencing vector. The vector pET28a(+) (Novagen, USA) carrying a kanamycin resistance marker and a cleavable His-tag was used for protein expression. *Phusion* DNA polymerase, dNTPs, various restriction enzymes and T4 DNA ligase (New England Biolabs, UK) were used for cloning experiments. TRIzol reagent (Life technologies US) was used for RNA isolation. 5′/3′ RACE second-generation kit and expand high fidelity PCR system (both Roche Diagnostics GmbH, Manheim, Germany) were used for isolation of full-length DnAR gene. NADH and NADPH (both ≥97% pure) (Sigma, USA) were used for enzyme activity measurements. Ni-NTA Agarose (Qiagen, Germany) was used as affinity matrix. Thrombin (Sigma, USA) was used for cleaving His-tag from DnAR-His₆ fusion protein.

5.2. Microorganisms and growth conditions

*D. nepalensis* NCYC 3413, previously isolated in our lab, was maintained on solid YPP (yeast extract 10 g l⁻¹, peptone 20 g l⁻¹, peptin 5 g l⁻¹ and agar 20 g l⁻¹) plates at 30 °C.35 The liquid media YPX (yeast extract 10 g l⁻¹, peptone 20 g l⁻¹ and xylose 20 g l⁻¹) with a loopful of inoculum was incubated at 30 °C, 180 rpm for 12 h, then harvested and gDNA and total RNA were isolated from the harvested cells. *E. coli* DH5α was used as the plasmid host. *E. coli* Rosetta was used for a heterologous expression of DnAR. *E. coli* strains were grown in Luria–Bertani medium under antibiotic control as per supplier’s instructions.

5.3. Molecular cloning of *D. nepalensis* AR

*D. nepalensis* gDNA was isolated by phenol chloroform method.36 The partial DnAR gene was amplified by PCR using *Tag* DNA polymerase and two primers, namely, F1 (5′-GTGGA-CATGGCCACCTTGTGC-3′) and R1 (5′-GACCAAGACTTGAGATT-CAACAAAT-3′), designed based on highly conserved regions of amino acid sequence found upon alignment of aldose (xylose) reductases from *D. Hansenii*, *C. tenuis*, *C. tropicalis*, *S. passalidarum*, *M. guillermondii* and *C. parapsilosis*. The DnAR
complete open reading frame (ORF) was determined by 5’ and 3’ RACE using 5’/3’ RACE second-generation kit (Roche Diagnostics GmbH, Manheim, Germany). RNA was isolated by TRIzol method and was used as a template. The obtained partial DnAR gene from gDNA was used for designing primers for RACE. For 5’ RACE, the gene-specific primers were SP1 (5’-GAGATGGGCTTCTCAAGAGATATTGTGCTATTCC-3’) and SP2 (1st nested) (5’-TTGAATTGAAGCATTCTAAAGCATTGATTACTCC-3’) and SP3 (2nd nested) (5’-GGAATTTGCTAATCCAAAGGACATTGCTATTCC-3’). For 3’ RACE, SP4 (5’-CGATGGGCAAAAGATATTGTGCTATTCC-3’) was used as the gene-specific primer. The obtained 5’ and 3’ RACE PCR products were cloned into pGEM-T easy vector. The full-length DnAR gene was then amplified using Tag DNA polymerase by overlap PCR with 5’ and 3’ RACE PCR products or directly from gDNA using two primers, namely, F2 (5’-GAATTTGCTATTGCTAACTGAGGATT-3’) and R2 (5’-CTAAGATTTGCTAACAGGTTAAGTGAATG-3’) with NdeI site (underlined) and EcoRI site (underlined). After that, the complete DnAR ORF was cloned into the expression vector pET28a(+), designated as pET28a-DnAR and sequenced. Standard protocols for nucleic acid manipulation and molecular cloning were used. DNA sequencing was performed at Eurofins Analytical Services India Pvt Ltd using Sanger sequencing method. Three clones were sequenced using both the vector-specific primers (T7 FF/RP) to ensure the correctness of AR sequence.

5.4. Heterologous expression of DnAR in E. coli Rosetta

Plasmid pET28a-DnAR was transformed into E. coli Rosetta (expression host) competent cells by heat shock. One of the colonies was inoculated into LB medium for preparing glycerol stocks and pre culture. Two percent of inoculum from pre culture stocks and pre culture. Two percent of inoculum from pre culture was transferred to the main culture and incubated till OD600 reached 0.7. The culture was transferred to the main culture and incubated till OD600 reached 0.7 and bound protein was then eluted by a gradient of 100, 200 and 300 mM imidazole in TBS buffer (each 5 ml) at a flow rate of ~0.25 ml min⁻¹. All of the fractions (flow through, 20, 100, 200, 300 mM imidazole elutions) flowing through the column were analyzed by SDS-PAGE. The fractions containing pure DnAR (100, 200 mM imidazole elutions) were collected and subjected to dialysis against 20 mM Tris–HCl buffer (pH 7.5) and stored in −80°C until use. Protein concentrations were estimated by bichoninic acid (BCA) assay with bovine serum albumin as a standard.

5.6. Aldose reductase assay and kinetic studies

Unless stated otherwise, the recombinant DnAR activity was determined spectrophotometrically (Perkin Elmer Lambda 25 UV/VIS spectrophotometer, USA) by monitoring the change in A340 in 500 μl reaction mixture containing 50 mM sodium phosphate buffer (pH 7.0), 0.3 mM NADPH as a cofactor and 300 mM xylose (a predominant pentose in lignocellulose) as a substrate at 45°C. The change in absorbance at 340 nm was measured continuously at least for 1 min at every 1 s time point. It was ensured by the addition of a specific amount of enzyme that gives a linear curve. NADPH molar extinction coefficient 6.22 mM⁻¹ cm⁻¹ was used for calculation of enzyme activity. One enzyme unit (U) was defined as the amount of enzyme that caused the oxidation of 1 μmol of NADPH per minute. Heat inactivated enzyme and 50 mM sodium phosphate buffer (pH 7.0) were taken for measuring auto hydrolysis of NADPH in the standard reaction mixture and considered as a reference. The kinetic parameters of cosubstrate NADPH were determined by measuring the initial velocities at constant xylose (160 mM) and different NADPH concentrations (0.01–0.6 mM). The substrate kinetic parameters were determined at constant NADPH (0.3 mM determined from previous experiments) and different substrate concentrations (5–800 mM). Sugar assayed were D-xylose, L-arabinose, D-ribose, D-galactose, D-glucose, D-fructose and D-mannose, whereas non-sugar carbonyl compounds assayed were glucaral, isosphathaldehyde, benzaldehyde, pyridine 3-carboxyaldehyde and 3-nitro benzoaldehyde. The obtained data were used to calculate the kinetic constants by fitting for the Michaelis–Menten equation using GraphPad Prism 5.

5.7. Effect of pH, temperature and metal ions

The effect of pH on enzyme activity was determined at 30°C by assay using a pH range from 4 to 10 using standard buffers namely, 50 mM sodium acetate (pH 4.0–5.5); 50 mM potassium phosphate (pH 6.0–8.0); 50 mM Tris–HCl (pH 8.5); and 50 mM glycine–NaOH (pH 9.0–10). To study the effect of temperature, the experiment was performed at optimal pH (determined from pH effect studies) and the enzyme assays were performed, at various temperatures ranging between 10 and 60°C. The effect of divalent metal ions (Ca²⁺, Cu²⁺, Fe²⁺, Mg²⁺, Mn²⁺, Ni²⁺ and Zn²⁺) was studied at different concentrations of metal ions (0.5,
1 and 2 mM) at optimal conditions and residual activities of recombinant DnAR were determined.

5.8. Salt tolerance and stability

The effect of salts on DnAR activity was determined by measuring the enzyme activity in the presence of different concentrations of NaCl and KCl up to 2 M at standard assay conditions. The enzyme kinetics using D-xylose as substrate was also performed in the presence of 0.5 M and 1.0 M NaCl/KCl respectively. The obtained data were used to calculate the kinetic constants by fitting for the Michaelis–Menten equation using GraphPad Prism 5 as described above. Salt stability of DnAR was assessed at 30 °C by incubating enzyme in the presence of 1 and 2 M of NaCl/KCl. Aliquots of enzyme at different time points were taken and specific activities were measured under standard assay conditions. The half-life of the enzyme was calculated by considering first order deactivation kinetics as described previously. To avoid the cumulative effect of temperature and salts, the salt stability studies were performed at 30 °C which was close to room temperature.

5.9. Far-UV CD spectra measurement in the presence of salts

The CD spectra were recorded using JASCO J-810 spectro-polarimeter (Easton, MD) at 25 °C with a thermostat cell holder connected to a Peltier temperature controller. The instrument was calibrated with 10-camphor sulphonlic acid before scanning the samples. A cuvette of 1 mm path length was used for scanning samples at a wavelength range of 250 to 200 nm to obtain CD spectra. The scanning was done at the scan speed of 10 nm min⁻¹ with a bandwidth of 2 nm. Average of three scans was taken for analysis. CD spectra were recorded using 3 μM protein in 10 mM sodium phosphate buffer (pH 7.0) at 0–2 M salt (NaCl/KCl), whereas the thermal unfolding of DnAR was analyzed from 20 to 80 °C using 6 μM protein in 10 mM sodium phosphate buffer (pH 7.0) at 0–2 M salt (NaCl/KCl). For determination of the thermal unfolding, the change in molar ellipticity at 222 nm was recorded continuously while the temperature was increased at the rate of 1.0 °C min⁻¹. Protein fraction unfolded was calculated using Gibbs–Helmholtz equation [ΔG = ΔH (1 – T/Tm) − ΔCp(ΔTm − T) + T ln(T/Tm)] where ΔG is the Gibbs free energy, ΔH the enthalpy, T the absolute temperature, Tm the T at which fraction folded is 0.5 and Cp the heat capacity] upon fitting the change of CD at a single wavelength as a function of temperature. The obtained data were analyzed using Boltzmann curve fitting function of Origin Lab software (v8.0773).

5.10. Homology modelling

A homology model of DnAR was built with SWISS-MODEL (v8.05) automated mode using the crystal structure of C. tenuis aldose (xylose) reductase (CtXR) bound to NADPH (PDB ID: 1K8C) as a template. The surface electrostatic potentials of DnAR model and CtXR crystal structure were calculated using Adaptive Poisson-Boltzmann Solver (APBS) tool in Chimera molecular modeling system with the PQR file generated using PDB2PQR online server.

5.11. Nucleotide sequence accession number

The nucleotide sequence of AR gene from D. nepalensis has been submitted to GenBank under the accession number KT239024.

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