

Effects of the polyhistidine tag on kinetics and other properties of trehalose synthase from *Deinococcus geothermalis*

Anna Panek, Olga Pietrow, Paweł Filipkowski and Józef Synowiecki✉

Department of Food Chemistry, Technology and Biotechnology, Faculty of Chemistry, Gdansk University of Technology, Gdańsk, Poland

Two recombinant trehalose synthases from *Deinococcus geothermalis* (DSMZ 11300) were compared. A significant influence of the artificial polyhistidine tag was observed in protein constitution. The recombinant trehalose synthase from *D. geothermalis* with His₆-tag has a higher K_m value of 254 mM, in comparison with the wild-type trehalose synthase (K_m 170 mM), and displayed a lower activity of maltose conversion when compared to the wild type. Moreover, differences in properties like temperature, pH, thermal- and pH-stability were observed. Presence of the histidine tag caused a decrease of thermal resistance in case of trehalose synthase with His₆-tag. These data confirmed a suggestion that the introduction of the histidine domain produces in some seldom cases undesirable changes in the protein.

Key words: *Deinococcus geothermalis*, trehalose synthase, influence of His₆-tag, trehalose, gene expression, *Escherichia coli*

Received: 23 November, 2012; **revised:** 25 April, 2013; **accepted:** 14 May, 2013; **available on-line:** 06 June, 2013

INTRODUCTION

Trehalose (α -D-glucopyranosyl-1,1- α -D-glucopyranoside) is a stable non-reducing disaccharide, which can be used in food, cosmetics, medical, and biotechnological industries, as well as for the stabilization of vaccines, enzymes, antibodies, hormones, pharmaceutical preparations, and organs for transplantations (Richards *et al.*, 1991; Higashiyama 2002; Berendsen 2002). Trehalose can create hydrogen bonds with protein and lipids, which stabilize their molecules and biological membranes (Lins *et al.*, 2004; Jain and Roy, 2008). Moreover, the formation of amorphous glass protects biological molecules during desiccation, freezing, heating, and oxidation (Crove and Crove, 2002; Banaroudi *et al.*, 2001).

Enzymes responsible for the one-step production of trehalose from maltose are trehalose synthases, EC 5.4.99.16. This process employs an inexpensive substrate derived from starch. Trehalose synthases are also characterized by amylase activity that converts glycogen into trehalose (Pan *et al.*, 2008). Trehalose synthases have been identified as sources of such bacteria as for instance the *Pseudomonas putida*, *Meiobacterium ruber*, *Thermus thermophilus*, *Deinococcus radiodurans* and *Arthobacter aureescens* (Ma *et al.*, 2006; Zdziebło & Synowiecki, 2006; Xiuli *et al.*, 2009; Filipkowski *et al.*, 2012; Zhu *et al.*, 2008).

In our previous work, as a new source of trehalose synthase, we used the extremophilic bacteria, *D. geothermalis* (Filipkowski *et al.*, 2012). This microorganism is a red-pigmented, Gram-positive, non-pathogenic, moderate thermophile extremely resistant to ionizing radiation,

ultraviolet light, and desiccation (Ferreira *et al.*, 1997). In our study, the gene encoding the trehalose synthase from *D. geothermalis* was cloned and expressed in *Escherichia coli*. This recombinant enzyme contains the His₆ tag, which simplified the enzyme purification using immobilized metal affinity chromatography (IMAC). The method for purifying proteins with histidine residues was first described by Hochuli *et al.* (1987). IMAC is based on the interaction between transitional metal ions, eg., Cu²⁺, Co²⁺, or Ni²⁺, immobilized on a matrix in a gelling agent, such as agarose or derivatized silica gel and proteins. The main amino acid in proteins that interacts with the immobilized transitional metal ions is histidine. Nowadays, more than 100 structures of His-tagged proteins have been deposited in the Protein Data Bank. In some seldom cases the affinity tag may interfere with protein activity (Wu & Filutowicz, 1999; Terpe, 2003). Usually, the fusion enzymes are as active as in case of wild proteins. However, in some cases the V_{max} for the tagged enzymes is 50% of the wild-type. Lowered activities are caused by insoluble inclusion bodies, misfolded conformation when expressed in *E. coli*, or different dimerization/oligomerization properties (Halliwell *et al.*, 2001; Pietzsch *et al.*, 2000; Wu & Filutowicz, 1999).

The previously obtained recombinant trehalose synthase from the *D. geothermalis* containing the polyhistidine domain had decreased the affinity to maltose. The purpose of this study was to produce a trehalose synthase destitute of histidine residues. Kinetic parameters between the wild-type enzyme and the recombinant protein with the polyhistidine tag were examined to compare their properties.

MATERIALS AND METHODS

Bacterial strains, plasmids, and culture conditions. *D. geothermalis* (DSMZ 11300, Braunschweig, Germany) was used as a source of the trehalose synthase gene. Bacterial cells were cultivated aerobically on a rotary shaker (Forma Orbital, Thermo Scientific, Marietta, OH, US) at 45°C (pH 7.2) in a modified medium recommended by the DSMZ as described previ-

✉ e-mail: jozsynow@pg.gda.pl

Abbreviations: K_m , Michaelis constant, V_{max} , maximum rate, *DgeoTreS*, trehalose synthase from *D. geothermalis* with His₆-tag, *DgeoTreSW*, trehalose synthase from *D. geothermalis* wild type, DSMZ, Deutsche Sammlung von Mikroorganismen und Zellkulturen, CD, Circular dichroism spectroscopy OD₆₀₀, optical density at $\lambda=600$ nm, PCR, polymerase chain reaction, DNA, deoxyribonucleic acid, EDTA, ethylenediaminetetraacetic acid, HPLC, high-performance liquid chromatography, SDS/PAGE, sodium dodecyl sulfate polyacrylamide gel electrophoresis

ously (Filipkowski *et al.*, 2006, Ferreira *et al.*, 1997). The *E. coli* TOP10F³ (Invitrogen, Carlsbad, CA) and Rosetta (DE3)pLysS (Novagen, Nottingham, United Kingdom) strains were used as a cloning host and an expression host, respectively. The *E. coli* cells with plasmids were cultured aerobically at 37°C to OD₆₀₀ of 0.6 in an LB medium supplemented with tetracycline (12.5 µg/mL) or chloramphenicol (34 µg/mL), respectively. The cells were harvested by centrifugation at 3000 × *g* for 10 min. The pJET (Fermentas UAB, Vilnius, Lithuania) and pET30Ek/LIC (Novagen, Darmstadt, Germany) plasmids were used for the construction of the expression system. Restriction enzymes were purchased from Fermentas.

Amplification of trehalose synthase (DgeoTreSW) gene. DNA from *D. geothermalis* isolated using a genomic DNA preparation kit (A&A Biotechnology, Gdańsk, Poland) was used for polymerase chain reaction (PCR) amplification with the following two primers:

5' aaaaCATATGACGCAAACCTCCACCTCCGAGT 3', and
5' tatCTCGAGTTACCGCACCCCGACAGC 3'

containing underlined recognition sites for restriction endonucleases, *NdeI* and *XhoI* (Fermentas, Lithuania). The reaction was performed using 250 ng of DNA, 10 pmoles of each primer, 12 µmoles of dNTPs, 12.5 µL 2 × PCR buffer (5 mM MgCl₂, 100 mM Tris, pH 9.0, 40 mM (NH₄)₂SO₄, 10 mM DMSO) and 0.5 µL Marathon DNA polymerase (*Pwo* & *Taq* polymerase mixture). After 1 min of preliminary heating at 95°C in a thermal cycler (EpGradient S, Eppendorf, Hamburg, Germany), each of 30 cycles was conducted 5-times at 95°C for 1 min, at 59°C for 1 min and at 72°C for 2 min, then 25-times at 95°C for 1 min, at 67°C for 1 min and at 72°C for 1.5 min, with a final step of 5 min at 72°C. The DNA fragment encoding *DgeoTreSW* was obtained and cloned into pJET vector following the steps described by the producer of the CloneJet kit (Fermentas). After sequencing and confirming the proper sequence, the DNA construct was digested with *NdeI* and *XhoI* restriction endonucleases and resubcloned into a pET30Ek/LIC vector. The digestion product, approximately below 1,700 bp, was isolated from an agarose gel bands using the Gel-Out kit (A&A Biotechnology).

Construction of expression vector. The competent cells *E. coli* TOP10F³ suspended in 1 mL 100 mM CaCl₂ were transformed by the ligation mixture for 1 h at 8°C, and after a heat shock (1.5 min at 42°C, then 1.5 min at 4°C) were incubated for 1 h at 37°C in 400 µL SOC medium (Invitrogen). The transformed *E. coli* cells plated on LB-agar tetracycline/kanamycin (tetracycline as described previously, kanamycin 20 µg/mL) plates were incubated at 37°C. After 16–18 h of growth, the obtained colonies were examined for the presence of trehalose synthase gene of *D. geothermalis* by PCR amplification and restriction analysis. The authenticity of the clone was ascertained by sequencing of the complete DNA fragment. The obtained construction, designated as pET30Ek/LICDgeoTreSW, was isolated and selected by electrophoresis on 1% agarose gel and then transformed into *E. coli* Rosetta (DE3)pLysS cells.

Expression of the wild-type trehalose synthase. A single colony of transformed *E. coli* from LB-agar plates was inoculated in a 50 mL liquid LB medium, supplemented with kanamycin/chloramphenicol, and cultivated at 37°C. When the OD₆₀₀ reached the value of about 0.6, the cell suspension was transferred to 2 L of LB medium containing kanamycin/chloram-

phenicol. The cultures were grown up to OD₆₀₀ of 0.6 at conditions described above. Then, the DgeoTreS expression in *E. coli* Rosetta (DE3)pLysS was induced at 37°C with isopropyl β-D-thiogalactopyranoside (IPTG) at the final concentration of 1 mM. The cells were harvested 3 h after induction by centrifugation, and the pellet washed with distilled water was centrifuged and stored at –20°C until use. SDS/PAGE separation of proteins was performed according to the method of Leammli (1970). The samples (10 µL) denatured by β-mercaptoethanol as a reducing agent and SDS were layered on the gel and separated using a voltage gradient of 15 V/cm. Protein bands were located by stained with Coomassie Brilliant Blue R250.

Isolation and purification of recombinant trehalose synthase. The transformed *E. coli* cells, harvested from 2 L of induced culture, were sonicated at 20 kHz (three times for 10 s in 30 s intervals) in 80 mL 10 mM phosphate buffer (pH 7.6) containing 1M EDTA, 100 mM CaCl₂, 0.1 mg lysozyme, and 1 mg RNase, using the Brenson Ultrasonic Sonifier II W250D (Geneve, Switzerland). The resulting mixture was centrifuged at 9000 × *g* for 40 min to give a clear supernatant. The protein fraction with trehalose synthase activity was precipitated by (NH₄)₂SO₄ to a final concentration of 20% (w/v). The centrifuged precipitate (9000 × *g*, 15 min) was dissolved in a small volume of citrate-phosphate buffer pH 7.2. Then, this fraction was purified, concentrated on the Centrifugal Filter Device (Amicon®Ultra-15 50 000 MWCO Carri-ghtwohill, Cork, Ireland), and after changing the buffer to physiological salt, used as a final preparation of the enzyme.

Enzyme assay. The activity of *DgeoTreSW* was determined by measuring the trehalose produced from maltose. The assays were initiated by the addition of 0.25 mL of *DgeoTreSW* solution to 1.0 mL of 0.3 M maltose solution in a 50 mM Britton-Robinson buffer (pH 7.6). The reaction at 40°C was terminated after heating the sample at 100°C for 10 min. The samples purified by centrifugation (9000 × *g* for 10 min) and filtration on a 0.2 µm Chromafil® PEF 20/25 filter (Machery-Nagel GmbH, Duren, Germany) were passed through a APS-2 HYPERSIL column (Thermo Electron Corporation, Dreiech, Germany) using acetonitrile/methanol/water (78:11:11, v/v/v) as mobile phase at a flow rate of 1.8 mL/min. The column temperature was 30°C. The amounts of the products formed during conversion of maltose were calculated from the area of the peaks obtained after sample separation by HPLC using a refractive index detector (La Chrom-7490, Merck, Hitachi, Tokyo, Japan). Trehalose, maltose, and glucose were used as standards at concentrations of 10 mg/mL.

The *DgeoTreSW* activity was expressed as the amount of enzyme that produces 1 µmol of trehalose per minute under described conditions. The relative enzyme activity (%) was defined as the percentage of enzyme activity in the control.

The temperature dependence of enzyme activity was assayed within the range of 5–70°C. The thermal stability of trehalose synthase was investigated by incubation of the enzyme solution in 50 mM Britton-Robinson buffer (pH 7.6) at 40°C, 55°C, and 60°C for different periods (up to 8 h). Protein concentrations (mg/mL) were determined by the measurement of absorbance at 280 using a Nano-Drop spectrophotometer (Thermo Fisher Scientific Inc. Wilmington, DE, US).

RESULTS AND DISCUSSION

Molecular cloning and characterization of His-tag free *DgeoTreSW*

Our previous experiments indicate that the recombinant trehalose synthase from *D. geothermalis* possessing His₆-tag (*DgeoTreS*) had decreased the affinity to maltose, and the K_m value was determined at 256 mM (Filipkowski *et al.*, 2012). It suggests an influence of this domain on enzyme activity. To examine the effect of the poly-histidine tag has on activity and kinetics of this protein we compared their properties to the wild-type enzyme (*DgeoTreSW*) from *D. geothermalis* expressed in *E. coli* Rosetta (DE3)pLysS. The region of *D. geothermalis* gene amplified by PCR had a sequence consisting of 1668 b.p. encoding 556 amino acid residues. Theoretical values of the molecular mass and isoelectric point of the wild-type enzyme were calculated to be 63.63 kDa and pI 4.92, respectively. These values estimated for the *DgeoTreSW* are slightly lower than those for *DgeoTreS*, due to the fact that the wild-type enzyme does not contain the His₆-tag preceded by Leu (L) and Glu (E) residues.

An optimal expression was achieved at 30°C after 4 h of induction by IPTG (Fig. 1). The wild-type trehalose synthase has been preliminary purified by thermal precipitation of *Escherichia coli* proteins. This step removes 66.35% of native *Escherichia coli* proteins. What is more, specific activity of cell-free extract increases from 0.0159 up to 0.0416 $\mu\text{mol}/\text{min}/\text{mg}$. Solubilized recombinant trehalose synthase was precipitated at 20% ammonium sulphate saturation. Dissolved precipitate was purified on a centrifugal filter device (Amicon Ultra-15 30000 MWCO). SDS/PAGE (Fig. 2) confirmed high purity of *DgeoTreSW* and their band was localized at the same place as his-tagged trehalose synthase. Among very intensive enzyme band only one weak band of other protein was visible. Such small amounts of other protein cannot influence the K_m value and their changes are caused by the polyhistidine tag.

Effect of His₆-tag on kinetic of maltose conversion

Compared to the K_m of trehalose synthase with poly-histidine tag (256 mM), the wild-type enzyme expressed in *E. coli* has a lower K_m of 170 mM. It suggests higher affinity of *DgeoTreSW* to maltose. Observed lower affin-

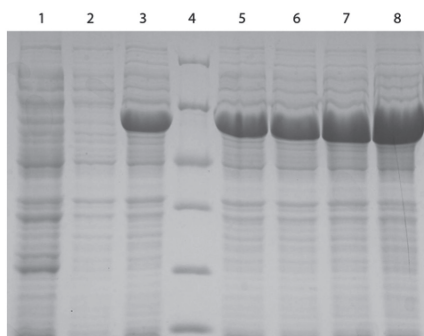


Figure 1. SDS/PAGE of protein in the fraction during the biosynthesis of the recombinant *DgeoTreSW*.

Lane 1, control *E. coli* strain with vector pET before induction; lane 2, recombinant *E. coli* strain with vector before induction; lane 3, cell extract after 3 h of protein expression induced by IPTG; lane 4, protein marker (Fermentas #SM0431); lane 5, cell extract after 4 h of protein expression induced by IPTG; lane 6, cell extract after 5 h of protein expression induced by IPTG; lane 7, cell extract after 6 h of protein expression induced by IPTG; lane 8, cell extract after 18 h of protein expression induced by IPTG.

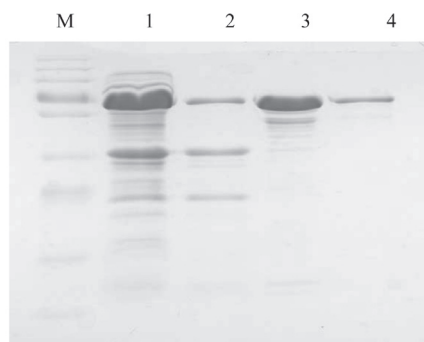


Figure 2. SDS/PAGE of proteins during the purification steps.

Lane M, protein marker (Page Ruler™ Plus (Thermo Scientific). Line 1, 10 μL cell free extract cells of *E. coli* Rosetta (DE3) *DgeoTreSW*. Line 2, 10 μL of cell free extract after heat treatment at 65°C for 10 min. Line 3, 10 μL of protein fraction precipitated at 20% $(\text{NH}_4)_2\text{SO}_4$ and purified on Amicon®, cut-off 100 kDa. Line 4, 10 μL *DgeoTreS* protein after metal affinity chromatography.

ity of *DgeoTreS* to substrate may be a result of possible changes of enzyme conformations caused by the His₆-tag. Recent reports also shown that His-tagged proteins are often expressed in *E. coli*, both in soluble form and insoluble inclusion bodies, limiting the amount of the enzyme accessible to the reaction (Halliwell *et al.*, 2001; Terpe, 2003; Khan *et al.*, 2012). According to the study of Khan *et al.* (2012) His-tag-free proteins have lower minima of CD spectrum at 208 and 222 nm, as compared with their His-tagged counterparts. It indicates a higher amount of α -helical content. Among the proteins investigated in our study, the catalytic efficiency (k_{cat}/K_m) value of *DgeoTreSW* was higher than that of *DgeoTreS*, indicating that *DgeoTreSW* is a better catalyst than trehalose synthase with the polyhistidine tag. The location of the hexa-histidine tag on the protein N-terminus or C-terminus also can influence the protein activity. The study on *DgeoTreS* with His₆-tag localized on the N-terminus is in progress and its results will appear elsewhere.

Changes of reaction conditions caused by His₆-tag

Figure 3 shows that the optimal temperature of maltose conversion into trehalose catalyzed by *DgeoTreS* was 40°C and it was increased up to 45°C in case of the wild-type enzyme. The thermostability of *DgeoTreSW* was higher in comparison with the enzyme containing the polyhistidine tag. After 8 h of heating at 55°C, the *DgeoTreS* retained about 57% of its maximal activity, whereas the *DgeoTreSW* was completely active (100%) after 8 h of incubation.

In comparison with the wild trehalose synthase indicating maximal activity at pH 7.1 in a 50 mM Britton-

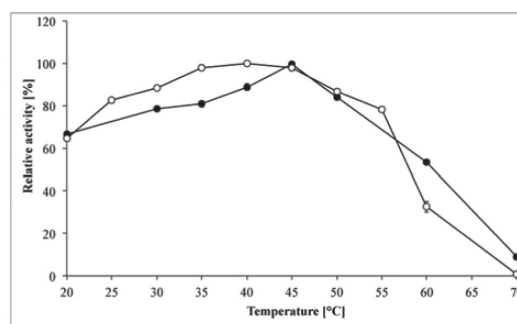


Figure 3. Optimal temperature of *DgeoTreS* (○) and *DgeoTreSW* (●) at pH 7.0.

The results are mean values of three replicates.

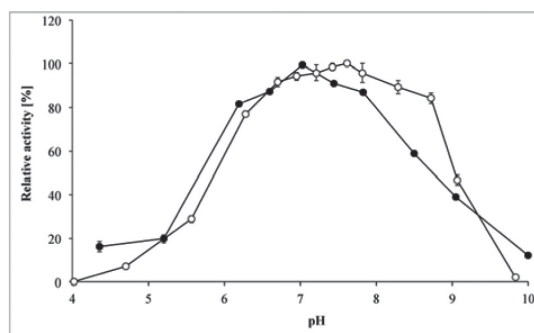


Figure 4. Optimal pH of *DgeoTreS* (○) and *DgeoTreSW* (●). The results are mean values of three replicates.

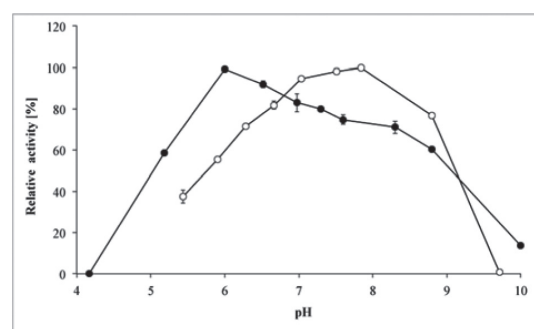


Figure 5. pH-stability of *DgeoTreS* (○) and *DgeoTreSW* (●). The pH stability was determined by measuring the residual activity after 1 h of incubation (40°C) in 50 mM Britton-Robinson buffers at various pH values. The results are mean values of three replicates.

Robinson buffer, the optimal pH for maltose conversion catalyzed by *DgeoTreS* was 7.6. These pH values are similar to those reported for trehalose synthases from *Pimelobacter* sp. R48 (Nishimoto *et al.*, 1996a) and *Thermus aquaticus* (Nishimoto *et al.*, 1996b). The investigated enzymes retained about 50% of maximal activity at a pH range of 6.0 to 9.0 (*DgeoTreS*), and 5.5 to 8.6 (*DgeoTreSW*) (Fig. 4).

To determine the effect of pH level on the stability of trehalose synthases containing polyhistidine tag or enzyme without this domain, the samples were incubated for 1 h at different pH levels adjusted by Britton Robinson buffers. The *DgeoTreS* had the highest remaining activity when incubated at pH 7.7, whereas the *DgeoTreSW* displayed maximal activity at the pH level of 6.0. Similarly to the *DgeoTreS*, the wild-type trehalose synthase was completely inactivated after the incubation at pH of about 4.2 and retained 85% of its maximal activity at the pH level of 7.0 (Fig. 5).

CONCLUSION

The present study leads to considerations about the influence of polyhistidine tags on kinetic parameters, and some properties of the recombinant trehalose synthase from *D. geothermalis*. The wild-type trehalose synthase exhibited higher activity when compared with his-tagged *DgeoTreS*, which had been studied previously. This report sends an important message that proteins containing His-tags may differ from their wild-type counterparts as far as their activity and other kinetic properties are concerned.

Acknowledgments

This work was financed mainly by the Polish National Science Centre.

REFERENCES

- Benaroudi N, Lee DH, Goldberg AL (2001) Trehalose accumulation during cellular stress protects cells and cellular proteins from damage by oxygen radicals. *J Biol Chem* **276**: 24261–24267.
- Berendsen DH (2002) Trehalose: a review of properties, history of use and human tolerance, and results of multiple safety studies. *Food Chem Toxicol* **40**: 871–898.
- Crove JH and Crove IM (2000) Preservation of mammalian cells, Learning on nature tricks. *Nat Biotechnol* **18**: 145–147.
- Ferreira AC, Nobre MF, Rainey FA, Silva MT, Wait R (1997) *Deinococcus geothermalis* sp. Nov. and *Deinococcus murrayi* sp. Nov. two extremely radiation-resistant and slightly thermophilic species from hot springs. *Int J Syst Bacteriol* **47**: 939–947.
- Filipkowski P, Duraj-Thatte A, Kur JW (2006) Novel thermostable single-stranded DNA-binding protein (SBB) from *Deinococcus geothermalis*. *Arch Microbiol* **187**: 129–137.
- Filipkowski P, Panek A, Felczykowska A, Pietrow O, Synowiecki J (2012) Expression of *Deinococcus geothermalis* trehalose synthase gene in *Escherichia coli* and its enzymatic properties. *Afr J Biotechnol* **11**: 13131–13139.
- Filipkowski P, Pietrow O, Panek A, Synowiecki J (2012) Properties of recombinant trehalose synthase from *Deinococcus radiodurans* expressed in *Escherichia coli*. *Acta Biochim Pol* **59**: 425–431.
- Halliwel CM, Morgan G, Qu CH-P, Cass AEG (2001) Introduction of a (poly)histidine tag in L-lactate dehydrogenase products a mixture of active and inactive molecules. *Anal Biochem* **295**: 257–261.
- Higashiyama T (2002) Novel functions and applications of trehalose. *Pure Appl Chem* **74**: 1263–1269.
- Hochuli E, Debeli H, Schacher A (1987) New metal helate adsorbent selective for proteins and peptide containing neighbouring histidine residues. *J Chromatogr* **411**: 177–184.
- Jain KN, Roy I (2008) Effect of trehalose on protein structure. *Protein Sci* **18**: 24–36.
- Khan F, Legler PM, Mease RM, Duncan EH, Elke S, Bergman-Leitner Angov E (2012) Histidine affinity tags affect MSP1₄₂ structural stability and immunobominance in mice. *Biotechnol J* **7**: 133–147.
- Laemmli UK (1970) Cleavage of structural proteins during the assembly of the head of bacteriophage T4. *Nature* **227**: 680–685.
- Lins RD, Pereira CS, Hünenberger PH (2004) Trehalose-Protein Interaction in Aqueous Solution. *Proteins* **55**: 177–186.
- Ma Y, Xue L, Sun DW (2006) Characteristic of trehalose synthase from permeabilized *Pseudomonas putida* cells and its application in converting maltose to trehalose. *J Food Eng* **77**: 342–347.
- Nishimoto T, Nakano M, Nakada T, Chaen H, Fukuda S, Sugimoto T, (1996a) Purification and properties of a novel enzyme, trehalose synthase from *Pimelobacter* sp. R48. *Biosci Biotechnol Biochem* **60**: 640–644.
- Nishimoto T, Nakada T, Chaen H, Fukuda S, Sugimoto T, Kurimoto M (1996b) Action of thermostable trehalose synthase from *Thermus aquaticus* on sucrose. *Biosci Biotechnol Biochem* **60**: 835–839.
- Pan Y, Carrol JD, Asano N, Pastuszak I, Edavana VK, Elbain AD (2008) Trehalose synthase converts glycogen to trehalose. *FEBS J* **275**: 3408–3420.
- Pietzsch M, Wiese A, Ragnitz K, Wilms B, Altenbuchner J, Mattes R, Syltatk C (2000) Purification of recombinant hydantoinase and L-N-carbamoylase from *Arthobacter aurescens* expressed in *Escherichia coli*: comparison of wild-type and genetically modified proteins. *J Chromatogr B* **737**: 179–186.
- Richards AD, Krakowska S, Dexter LB, Schmid H, Wolterbeek APM, Waalkens-Roser B (1991) Trehalose, a new approach to premium dried foods. *Trends Food Sci Technol* **2**: 166–169.
- Terpe K (2003) Overview of tag protein fusions: from molecular and biochemical fundamentals to commercial systems. *Appl Microbiol Biotechnol* **60**: 523–533.
- Wu J, Filutowicz M (1999) Hexahistidine (His₆)-tag dependent protein dimerization: A cautionary tale. *Acta Biochim Polonica* **46**: 591–599.
- Xiuli W, Hongbiao D, Ming Y, Yu Q (2009) Gene cloning, expression and characterization of a novel trehalose synthase from *Arthobacter aurescens*. *Appl Microbiol Biotechnol* **83**: 477–482.
- Zdzieblo A, Synowiecki J (2006) Production of trehalose by intramolecular transglucosylation of maltose catalyzed by a new enzyme from *Thermus thermophilus*. *Food Chem* **96**: 8–13.
- Zhu Y, Zhang J, Wie D, Wang Y, Chen X, Xing L, Li M (2008) Isolation and identification of a thermophilic strain producing trehalose synthase from geothermal water in China. *Biosci Biotechnol Biochem* **72**: 2019–2024.