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**Enhanced arginine biosynthesis and lower proteolytic profile as indicators of *Saccharomyces cerevisiae* stress in stationary phase during fermentation of high sugar grape must: A proteomic evidence**

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(Article begins on next page)

1 **Enhanced arginine biosynthesis and lower proteolytic profile as indicators of *Saccharomyces***  
2 ***cerevisiae* stress in stationary phase during fermentation of high sugar grape must: a proteomic**  
3 **evidence.**

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**ABSTRACT**

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25 A strain of *Saccharomyces (S) cerevisiae* (ISE19), which displayed an initial good adaptation to a  
26 high sugar medium with increased acetate and glycerol production but weak overall  
27 growth/fermentation performances, was selected during the alcoholic fermentation of Cortese grape  
28 must. To obtain insights into the metabolic changes that occur in the must during growth in particular  
29 conditions (high ethanol, high residual sugars and low nitrogen availability) leading to a sluggish  
30 fermentation or even fermentation arrest, comparative in-gel proteomic analyses were performed on  
31 cells grown in media containing 200 g/L and 260 g/L of glucose, respectively, while the YAN (Yeast  
32 Assimilable Nitrogen) concentration was maintained as it was. Two post-translationally different  
33 arginine synthases (pI<sub>s</sub> 5.6 and 5.8) were found in higher abundances in the high glucose-grown cells,  
34 together with an increased abundance of a glycosyltransferase involved in cell-wall mannans  
35 synthesis, and of two regulatory proteins (K7\_Bmh1p and K7\_Bmh2p) that control membrane  
36 transport. In parallel, a proteinase K-like proteolytic enzyme and three other protein fragments  
37 (Indolepyruvate decarboxylase 1, Fba1p and Eno1p) were present in lower abundances in the high  
38 glucose condition, where oxidative stress and cell cycle involved enzymes were also found to be less  
39 abundant. The overall results suggest that in stationary phase stress conditions, leading to stuck  
40 fermentation, *S. cerevisiae* ISE19 decreases cell replication, oxidative stress responses and proteolytic  
41 activity, while induces other metabolic modifications that are mainly based on cell-wall renewal,  
42 regulation of the solute transport across the cell membrane and *de novo* arginine synthesis.

43 **Key words:** *in-gel*-proteomics, glycolytic enzymes, cell-wall mannans, proteins controlling stress-  
44 induced apoptosis, K7\_Bmh.

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**HIGHLIGHTS**

- 48 • The paper describes what happens at a proteomic level when *S. cerevisiae* ISE19 is grown in  
49 high sugar grape musts in a condition leading to a fermentation arrest.
- 50 • A decreased abundance of proteolytic enzymes and enzyme fragments was observed in a high  
51 sugar condition, in agreement with recent literature data that have reported how the low  
52 expression of proteases in glucose-rich musts can cause the arrest of alcoholic fermentation.
- 53 • An increased abundance of cell-wall renewal enzymes and of the proteins that regulate  
54 membrane transport underline an effective stress response concerning envelope structures.
- 55 • Apart from proline, arginine could also play a direct protective role against osmotic stress in  
56 *S. cerevisiae* ISE19 (as previously demonstrated for cold stress), since its biosynthetic  
57 pathway seems to be activated.

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## INTRODUCTION

70 During industrial processes, and in particular during alcoholic fermentation, microorganisms  
71 encounter several stressors that can compromise their life, their performances and the achievement of  
72 satisfactory amounts of the desired end-product. The most common environmental factors that can  
73 affect yeasts growth and end-product biosynthesis are must pH, temperature, redox potential and  
74 osmolarity (Auesukaree, 2017; Matallana and Aranda, 2017). *Saccharomyces cerevisiae* is the most  
75 prominent microorganism involved in wine production. During alcoholic fermentation, the microbial  
76 growth phases are characterized by different metabolic events. During the lag-phase, yeast cells adjust  
77 their metabolism to adapt to the high initial glucose/fructose concentrations and to be able to grow  
78 and convert these sugars into ethanol. One-third of the total ethanol and most of the glycerol amounts  
79 are produced in the exponential phase, in parallel with the/an increase in biomass. The remaining two  
80 thirds of ethanol are generated in the stationary phase, together with the aromatic compounds that  
81 determine the final sensory profile and quality of the wine (Salmon and Barre, 1998). In all these  
82 stages, yeast cells undergo stress such as: I) low temperatures (Pizarro et al, 2008), II) osmotic stress  
83 (Yale and Bohnert, 2001), III) anaerobiosis (Kwast et al., 2002) IV) lack of nutrients (Boer et al.,  
84 2003) and V) ethanol stress (Alexandre et al., 2001).

85 It is well known that a too high osmotic strength (high solute-low solvent concentration) can  
86 damage microbial physiology, above all by subtracting the solvation water that stabilizes the tertiary  
87 and quaternary structures of proteins (Goldbeck et al., 2001). A salty or sugar-rich environment  
88 prevents or delays growth (Hohmann, 2002). Some aspects of microbial responses to osmotic stress  
89 have long been elucidated: for instance, salt damage is linked to an altered ionic strength, whereas a  
90 high sugar content can cause osmotic stress, without altering the surface charges of the  
91 macromolecules (Lages et al., 1999).

92 As far as yeasts are concerned, it has been established that cells exposed to hyperosmotic NaCl  
93 concentrations adapt by increasing glycerol uptake inside the cell (Lages et al, 1999), or they die  
94 through an apoptotic process (Huh et al, 2003). However, this apoptotic process is the consequence

95 of an ion disequilibrium rather than of hyperosmotic stress. It has been demonstrated that sugar  
96 hyperosmotic stress (70% glucose or sorbitol w/w) can induce both morphological (chromatin  
97 condensation along the nuclear envelope, mitochondria swelling, DNA strand breaks) and  
98 biochemical (reactive oxygen species (ROS) production, meta-caspase activation) events that lead to  
99 cell apoptosis. Cell death is growth-phase dependent, with stationary cells displaying the highest  
100 death rate (Silva et al., 2005).

101         Ethanol stress affects cell viability to a great extent at the final phase of batch fermentation.  
102 Toxicity is mainly due to the interaction of ethanol with the cytoplasmic membrane (and, to a lesser  
103 extent, to cytosolic enzyme damage). The action of ethanol on both the phospholipid heads and  
104 membrane proteins is counteracted by the cell, primarily through membrane-level modifications.  
105 Increases in the content of unsaturated fatty acids and ergosterol and reductions in the membrane  
106 protein content are the best known yeast responses to ethanol stress (Vanegas et al, 2012). These  
107 changes lead to consequences such as: i) variation of the proton flow, which in turn impairs pH  
108 homeostasis, ii) reduced capability of  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  translocation, iii) impaired activity of active  
109 membrane transporters (Bisson, 1999). The overall result is an alteration of membrane fluidity that  
110 strongly affects the trafficking capability of the cell.

111         In a previous investigation, conducted in the very early stages of fermentation, metabolites  
112 and transcripts were evaluated for several yeasts strains grown in a hyperosmotic medium (Noti et  
113 al., 2015). A high glycerol and acetate producer, that is *S. cerevisiae* (strain ISE19), was detected.  
114 This phenotypic trait correlates with an initial good growth and alcohol production in a sugar rich  
115 environment, but then with weaker performances when the simultaneous effects of prolonged  
116 hyperosmosis, an increasing ethanol concentration and a low nitrogen content are present. These  
117 stressing conditions, which occur in most fermentations with a high sugar content, frequently lead to  
118 stuck or sluggish fermentations (Bisson, 1999). The present research is aimed at shedding light on  
119 the effects triggered by the late fermentation phase stress on the protein profiles of *S. cerevisiae*

120 *ISE19*. An in-gel approach was applied to compare the proteomes of high sugar grown cells and  
121 control cells both harvested in stationary phase, in order to identify metabolic indicators of cell stress  
122 in the incoming sluggish or arrested fermentation

## 123 **MATERIALS AND METHODS**

### 124 ***Overall strategy***

125 Comparative proteomic analyses of a high glycerol and acetate producer, namely, the *S.*  
126 *cerevisiae* strain ISE 19, which belongs to the CREA-Centro di Ricerca Viticoltura ed Enologia  
127 culture collection (Asti, Italy), and which was grown in natural Cortese must with both a regular and  
128 a high sugar content, in the advanced phases of fermentation, have been performed.

### 129 ***Fermentation conditions***

130 *S. cerevisiae* ISE 19 was pre-cultured in YPD at 26°C for 48 h. It was subsequently inoculated,  
131 at a concentration of  $5 \times 10^6$  cell/mL (total cell), in 0.22  $\mu$ m filter sterilized Cortese white grape must  
132 (800 mL of culture). The main parameters of the must were: pH 3.30, 200 g/L of reducing sugar and  
133 200 mg/L of Yeast Assimilable Nitrogen (YAN). Two different conditions were tested in the  
134 comparative proteomic study. The former (ISE19g-) was tested with a regular amount of sugar (200  
135 g/L), and the latter (ISE19g+) was tested by adding glucose/fructose 50% w/w to the must to reach  
136 260 g/L of sugar and by restoring the YAN to 200 mg/L. Fermentations were performed at 20°C  
137 without stirring, and three biological replicates were set up. Samples were harvested during  
138 fermentation: growth was estimated by optical density (OD) at 600 nm calculating cell/mL by  
139 calibration curve done with Bürker chamber count, ethanol and acetate were determined by enzymatic  
140 analysis (R-Biopharm AG, Darmstadt, Germany), the residual sugar content (glucose and fructose)  
141 and glycerol were evaluated by means of an HPLC equipped with a refractometric detector, using a  
142 Rezex RCM-Monosaccharide column (dimension: 300 x 7.8 mm; particle size 8  $\mu$ m; Phenomenex,  
143 Torrance, USA). The adopted conditions were the following: eluent: water; column temperature:  
144 85°C; flow: 0.35 mL/min; injection volume: 20  $\mu$ L. Samples for the proteomic analyses were

145 harvested at 175 g/L of consumed sugar(s), at 11 days of fermentation for ISE19g+ and 14 days of  
146 fermentation for the ISE19g- test. Samples were pelleted and immediately frozen. At this  
147 fermentation stage, residual sugar contents of 25 g/l and of 85 g/l were present in the low and high  
148 sugar media, respectively.

#### 149 *Preparation of the protein extracts*

150 Yeast cells (50 mL of about  $9 \times 10^7$  total cells/mL) were washed with 50 mL of a 0.85% NaCl  
151 solution, centrifuged (5000xg for 20 min) and the supernatant was discarded. Cell lysis was obtained  
152 by re-suspending the pellet with 3 mL of lysis buffer (Tris-HCl 50 mM, pH 7.3, EDTA 1mM), and  
153 by adding an equal volume of 0.5 mm glass beads to break the cells (10 cycles of 20 minutes on ice,  
154 vortexing at maximum speed). At the end of the procedure, centrifugation was carried out (5000xg  
155 for 20 minutes at 4°C), and the supernatant was transferred to a new vial for total protein  
156 quantification.

157 Protein quantification was performed using the "2D Quant kit" (GE Healthcare) (UV analysis  
158 at 480 nm), according to the manufacturer's instructions. After the preliminary preparation, protein  
159 samples were ultra-centrifuged (100000xg for 1 hr. at 4°C) in a Beckman L8-60M Ultracentrifuge  
160 (Type 60 rotor). The supernatant containing the soluble proteins was recovered, supplemented with  
161 10 µL/mL of Nuclease Mix (GE Healthcare) and dialyzed/concentrated against four volumes of  
162 bidistilled water in 10 KDa membrane cutoff tubes (Amicon), at a final volume of 1 mL. A second  
163 quantification was performed, followed by methanol/chloroform protein precipitation, according to  
164 Wessels and Flugge (1984). The obtained pellet was then solubilized in a rehydration solution (6.5  
165 M urea, 2.2 M thiourea, 4% w/v CHAPS, 5 mM Tris-HCl, pH 8.8, 0.5% IPG buffer (GE Healthcare),  
166 100 mM DTT). The protein concentration was evaluated again by using the 2D Quant kit (GE  
167 Healthcare).

168 *Two dimensional electrophoresis*

169 Isoelectric focusing

170 Thirteen cm long strips were used, over a 4-7 pH range, for Isoelectric Focusing (IEF). Three  
171 technical replicates were performed for each of the three biological replicates in the two different  
172 fermentation conditions (glucose-enriched and control). About 275 µg of extracted proteins was  
173 loaded for each strip. IEF was performed using IPGphor (GE Healthcare) at 20°C, with 66.000 Vh,  
174 at 8000 V, after 10 h of active rehydration (50 V).

175 The IEF strips were then incubated at room temperature for 15 min in a reduction buffer (6 M  
176 urea, 30% v/v glycerol, 2% w/v SDS, 50 mM Tris-HCl pH 8.6), and enriched with 10 mM DTT. They  
177 were subsequently incubated for 15 min in an alkylation buffer (6 M urea, 30% v/v glycerol, 2 w/v  
178 SDS, 50 mM Tris-HCl pH 8.6), and enriched with iodoacetamide 4.5% w/v to alkylate the sulfide  
179 groups and prevent re-oxidation during electrophoresis.

180 SDS-PAGE

181 After equilibration, the strips were sealed at the top of 1.00 mm vertical second dimension  
182 gels with 0.5% of boiling agarose. SDS-PAGE was carried out for each sample on 11.5% T and 3.3%  
183 C acrylamide (Biorad) on homogeneous gels. The running buffer was 25 mM Tris, 192 mM glycine,  
184 0.1% SDS, pH 8.3. The running conditions were: 600 V constant voltage, 20 mA/gel, 60 W for 15  
185 min at 15°C, 600 V constant voltage, 40 mA/gel, and 80 W for about 2.5 h at 15°C. The used  
186 molecular weight marker was a Low  $M_r$  Electrophoresis Calibration Kit (GE Healthcare).

187 The gels were automatically stained, using Processor Plus (Amersham Biosciences), with  
188 freshly prepared Colloidal Coomassie Blue stain (Neuhoff et al., 1988). After 12 hours of staining, the  
189 gels were dried in a GD 2000 Vacuum Gel Drier System (GE Healthcare).

190 ***Image analysis***

191 2-DE gel images were acquired using a SI Molecular Dynamics Personal Densitometer  
192 (Amersham Biosciences). Image analysis was performed using the Progenesis PG 220 software (Non  
193 Linear Dynamics). Spot detection was automatically performed using the 2005 detection software  
194 algorithm.

195 ***Statistical analysis***

196 Nine replicates were performed for each 2-DE gel, and for each condition (high and normal  
197 sugar contents in the culture media): three analytical replicates were conducted for each biological  
198 replicate. Spot intensities were measured, *via* normalized spot volumes, using the "total quantity in  
199 valid spot" standardization system. The spot volumes were statistically analyzed by means of the  
200 Student's *T-test*: the mean values were considered significantly different when  $p < 0.05$ . Protein spots  
201 with a fold change  $\geq 2$  and  $p < 0.05$  were selected for MS analysis.

202 ***Mass spectrometry analysis and protein identification***

203 The selected spots were identified by means of MALDI-TOF/TOF mass spectrometry, using  
204 an Ultraflex III MALDI TOF/TOF instrument (Bruker Daltonics, Bremen). The spots withdrawn  
205 from the 2DE gels were destained overnight (with a 50 mM ammonium bicarbonate and 40% v/v  
206 ethanol solution), washed three times for 10 min with acetonitrile and then dried in a Speedvac device.  
207 The proteins were *in gel* digested with trypsin (Promega, Madison, USA), and their spectra were  
208 acquired as described by Zava *et al.* (2009). The MS-Fit software package (<http://prospector.ucsf.edu>)  
209 was used to search against the NCBI 2015.3.10 database, using the peptide mass fingerprinting  
210 method (PMF) (Pappin *et al.*, 1993). The following parameters were set for the searches: S-  
211 carbamidomethyl deriviate on cysteine as a fixed modification, oxidation on methionine as a variable  
212 modification and two missed cleavage sites for trypsin digestion. The peptide mass tolerance was 20  
213 ppm.

## RESULTS

214

### 215 Fermentation performance

216 Figure 1 shows the fermentation profiles of the two tested conditions (with or without added sugars),  
217 which were obtained by monitoring sugar consumption and ethanol production. The fermentation of  
218 Cortese must with the added sugars, initially shows a better performance with a higher daily rate of  
219 ethanol production. The conversion of the sugars into ethanol slowed down from the eleventh day of  
220 fermentation onwards, until it reached a complete stop on the eighteenth day of fermentation. Stuck  
221 fermentation occurred at an alcohol content of about 13.40 vol%, with 36 g/L of residual sugar,  
222 mainly consisting of fructose. The fermentation profile of the must not supplemented with sugars was  
223 regular, with complete exhaustion of the residual sugars and a final ethanol concentration of about  
224 12% (v/v). The growth kinetics in the two conditions (Fig. 2) showed a higher yeast population in the  
225 supplemented must, which reached a maximum of about  $120 \times 10^6$  cell/mL after six days of  
226 fermentation, whereas the must without any sugar addition underwent a maximum growth of  $100 \times$   
227  $10^6$  cell/mL, which was reached after seven days of fermentation. From the 14<sup>th</sup> day onwards, the  
228 yeast population tended to decrease in both sugar conditions reaching similar values on day 21.

229 Glycerol and acetate production differed in the two tests in relation to the initial sugar content (Fig.  
230 3). In grape must with higher sugar concentrations, yeasts showed an acetic acid production rate  
231 constantly higher as compared to the fermentation with regular sugar, reaching  $0.60 \pm 0.03$  (SD) g/L  
232 after 7 days. Later, acetate accumulation proceeded slower, showing, at the end of fermentation,  
233 concentration of  $0.68 \pm 0.03$  g/L (Fig. 3). Regular sugar test showed a decrease in the acetate  
234 production rate after 3 days and reached a maximum of  $0.5 \pm 0.02$  g/L acetate at the end of the  
235 fermentation. Similarly, the test with added sugar exhibited a higher concentration also for glycerol  
236 that occurs since the beginning of the fermentation and reached  $7.0 \pm 0.12$  compared to a max of  $6.30$   
237  $\pm 0.28$  in fermentation with regular sugar. However, glycerol showed a more regular biosynthetic rate  
238 as compared to the production of acetate and its concentration remains stable under both conditions  
239 (high and low sugar) after 9 days of fermentation (Fig. 3)

## 240 **Comparative proteomic studies**

241 Protein profiles of the high glycerol and acetate producer *S. cerevisiae* ISE 19 grown in regular  
242 (ISE19g-) and high (ISE19g+) sugar contents, respectively, have been analyzed at a critical moment  
243 of the cell growth, that is, when the simultaneous presence of osmotic stress, ethanol stress and  
244 nitrogen depletion occurs. Samples were harvested at the stationary phase (Fig. 2), when 10.5%  
245 vol/vol of ethanol was produced in both conditions, whereas the remaining residual sugars were 25  
246 and 85 g/L in ISE19g- and ISE19g+, respectively (Fig. 1). Protein concentrations at the end of the  
247 extraction process were  $9.97 \pm 0.71 \mu\text{g}/\mu\text{L}$  in ISE19g- and  $11.78 \pm 0.75 \mu\text{g}/\mu\text{L}$  in ISE19g+.  
248 Comparative proteomic analyses were performed on the total cell protein extract (*in toto* proteome)  
249 in the acidic pI range (pH 4-7), where most yeast proteins can be found, in order to detect the presence  
250 of the differentially abundant proteins.

## 251 **Protein identification**

252 The 2DE allowed a good protein separation degree to be obtained for each considered sample.  
253 Image analysis of the 2DE gels revealed differences in spot intensity in the two experimental  
254 conditions. (Figure 4).

255 At first sight, a greater total protein pool abundance in gels loaded with extracts from cells  
256 grown in high sugar condition is detectable. Image analysis revealed 28 statistically significant  
257 different abundant spots. Three spots were absent in the high sugar condition and four spots were  
258 present exclusively in the high sugar condition. Of the remaining spots, 7 were present in higher  
259 abundances and 14 in lower abundances in the condition stimulated with a high sugar content. The  
260 spot identifications and assignment of the proteins to specific metabolic pathways are shown in Table  
261 1.

## 262 **DISCUSSION**

263 The protein expression profiles of *S. cerevisiae* ISE19, in an advanced stage of must fermentation  
264 with different initial sugar concentrations, have been analyzed in this work. The imbalance condition

265 between the must sugar content and the presence of Yeast Assimilable Nitrogen (YAN) has been  
266 recognized as being the primary cause of fermentative arrests, even though the molecular mechanisms  
267 involved in sluggish fermentation and the arrest of fermentation are still unclear (Bisson 1999).

268 In the present study, the fermentation with the higher sugar content initially showed a better  
269 performance, both in terms of ethanol production and cell growth, with respect to the control  
270 conditions. The difference of 60 g/l in the initial juice sugar load did not result in any extension of  
271 the lag phase, thus demonstrating strain response capacity toward the high initial osmotic pressure.  
272 At this early stage, the ISE19 strain was probably favored by a higher carbon source availability,  
273 whereas the nitrogen concentration was not yet a limiting factor. The stuck fermentation, which  
274 occurred at 13.40% ethanol at the end of the stationary phase, was presumably due to the low nitrogen  
275 availability, which is known to be a strong limiting factor (Christ et al., 2015). Actually, owing to the  
276 higher sugar concentration and the good osmotolerance of this strain, the biomass yield was higher.  
277 In this condition, there is an increased need of nitrogen to support growth. Moreover, the concomitant  
278 presence of several stressors, that is, a high ethanol content, the osmotic pressure of the residual sugars  
279 and the accumulation of toxic compounds, such as medium-chain fatty acids, may have contributed  
280 to the slowing down of the fermentative efficiency, as previously suggested by other authors (Lafon-  
281 Lafourcade et al., 1984, Borrull et al., 2015). When fermentation arrest was observed, the main sugar  
282 present was fructose (data not shown), due to the lower affinity of the hexose transporters (HXT) with  
283 fructose and the differences in the efficiency of the hexokinases (HXK) activity toward this sugar  
284 observed in yeasts (Bisson, 1999, Berthels et al., 2008).

285 *S. cerevisiae* cells react to stress through general and/or specific response mechanisms. Global  
286 changes in the majority of transcripts have been observed during the fermentation process of wine  
287 making, thus highlighting a general adaptive response to the typical stressors of alcoholic  
288 fermentation (Marks et al., 2008). In the early fermentation stages, the greatest environmental  
289 constraint is osmotic stress, which generates a water flow from inside to outside the cytoplasmic

290 membrane. Later, the yeast cell adapts itself through multi-level specific response mechanisms  
291 (Hohmann, 2002; Yanget al., 2006, Zuzuarregui et al., 2006; Tapia et al., 2015). However, the main  
292 response of yeast cells to high-osmolarity is the production of glycerol, the best osmotic balance  
293 stabilizer (Hohmann, 2002). Glycerol accumulation has been shown to account for 95% of the internal  
294 osmolarity recovery (Reed et al., 1987).

295         It should be underlined that, from a metabolic standpoint, glycerol can originate from  
296 glycolysis, at the expense of the biomass, by diverting dihydroxyacetonephosphate (DHAP) from the  
297 glycolytic flux after sensing altered osmolarity (Remize et al., 2003; Capaldi et al., 2008), thus  
298 performing the so-called glyceropyruvic fermentation (Fig 5). However, during hyperosmotic stress,  
299 yeasts can also enhance the intracellular glycerol content by limiting the glycerol flux outside the  
300 cytoplasmic membrane with closure of aquaglyceroporin Fps1 channels (Oliveira et al., 2003) and  
301 activating synthesis of glycerol transporters encoded by the *STL1* gene (Petelenz-Kurdziel et al.,  
302 2013). These proton symport systems can enhance the active uptake of external glycerol, which in  
303 turn is used both as a carbon source and during adaption to osmotic stress (Ferreira et al., 2005) and  
304 temperature (Tulha et al., 2010). Transcriptional and non-transcriptional mechanisms are involved in  
305 these flux regulations (Hohmann, 2009; Ahmadpour et al., 2014). Along with the osmo-adaptation  
306 mechanism, glycerol production during fermentation is the result of the redox balance control  
307 mechanism set up to oxidize the excess of NADH produced in the formation of 1,3-  
308 diphosphoglycerate starting from the 3-phosphate glyceraldehyde in glycolysis (Ansell et al., 1997).  
309 On the other hand, in order to balance the excess of NAD<sup>+</sup> generated by the initial formation of the  
310 osmo-protective glycerol, the cell utilizes NAD<sup>+</sup> dependent *aldehyde dehydrogenases*, synthesizing  
311 acetate (Navarro-Aviño et al., 1999, Pigeau and Inglis, 2005). In the present investigation, the higher  
312 glycerol and acetate production observed in must with added sugar reflects the mechanism for  
313 adaptation to hyperosmosis and the successive redox regulation during alcoholic fermentation  
314 according to the mechanisms outlined above.

315 No apparent modifications concerning the glyceropyruvic pathway (Fig 4) were observed, at  
316 a proteomic level (Tab.1), after prolonged exposure of *S. cerevisiae* ISE 19 to high sugar environment  
317 in a condition of incoming sluggish and stuck fermentation. As far as the functional state (open or  
318 closed) of the aquaglyceroporin Fps1 channels is concerned, no conclusion can be reached from the  
319 proteomic studies. However, the regulatory proteins K7\_Bmh2p (spot 1687B) and K7\_Bmh1p (spot  
320 1689B), which control the formation of the vesicles involved in transport and exocytosis, were found  
321 to be present, but only in the hyperosmotic condition. These proteins, which belong to the 14-3-3  
322 gene family, are also involved in the protection against stress-induced apoptosis, and they play an  
323 important role in the post-transcriptional control of yeast proteins (Clapp et al., 2012).

324 Peculiar results concerning glycolysis are worth discussing. Three enzymes of the alcoholic  
325 fermentation pathway were present, with higher abundance in the sugar-stimulated condition:  
326 fructose biphosphate aldolase (Fba1p) (spot 1415B), phosphopyruvate hydratase (Eno 2 p) (spot  
327 1378B), and pyruvate decarboxylase (Pdc1p) (spots 1331B, 1564B and 1569B). The latter enzyme,  
328 converting pyruvate into acetaldehyde and having TPP as a cofactor, was present in three spots  
329 displaying different isoelectric points (6.1, 5.8 and 5.9 respectively) and the same molecular weight,  
330 thus suggesting that they are the result of post-translational modifications of the same gene product.  
331 As far as the other two enzymes are concerned, the higher abundance of Fba1p can be exploited to  
332 supply more DHAP for glycerol biosynthesis whose greater production has actually been observed in  
333 yeasts during high sugar fermentation (fig. 3b). The higher abundance of Eno2p is in agreement with  
334 the fact that Eno2p is the true glycolytic enzyme, and that glucose can act as an inducer of its  
335 synthesis, as previously observed (Kornblatt et al., 2013).

336 Other enzymes involved in glycolysis/alcoholic fermentation are present in lower abundances  
337 in high osmotic condition-grown yeasts. The low level of enolase Eno1p (spot 1434A) (25 fold less  
338 abundant in high glucose) is consistent with the known repression on the encoding gene exerted by  
339 glucose (Kornblatt et al., 2013). Previous studies showed that Eno1p (as well as the oxidative alcohol

340 dehydrogenase ADH<sub>2</sub>) is more abundant in yeast cells grown in media containing ethanol, thus  
341 suggesting a gluconeogenic rather than a glycolytic role (Futcher et al., 1999). Two triose-phosphate  
342 isomerase Tpi1 (spot 1519A) and Tpi1p (spot 1515A) enzymes, with different entry codes  
343 (NP\_010335 and EGA87556 respectively) (probably the products of two different genes), were  
344 present in low abundance. Triose phosphate isomerase has the function of maintaining a correct  
345 balance between glyceraldehyde phosphate (GAP) and DHAP (derived from fructose 1,6  
346 biphosphate), and of supplying glycolysis with GAP. A part of the DHAP is probably necessary, in  
347 the hyperosmotic condition, to feed the glyceropyruvic route (Fig.5), hence triose phosphate  
348 isomerase has to work at a basal level to prevent all the DAPH from being converted into GAP. Three  
349 spots (1396A 1400A and 1419A), corresponding to oxidative alcohol dehydrogenases (ADHs), were  
350 found to be of low abundance in high glucose-medium grown cells. The inhibition of oxidative ADHs,  
351 together with the enhanced abundance of pyruvate decarboxylase, suggests the activation of alcoholic  
352 fermentation.

353         The overall results concerning glycolysis (in the cells grown in the hyperosmotic medium)  
354 suggest: i) an initial activation of the glycolytic flux, due to an enhanced abundance of fructose 1,2  
355 biphosphate aldolase, ii) a slight slowing-down of glycolysis, due to a decreased abundance of triose-  
356 phosphate isomerase, which probably favors glycerol synthesis and iii) an activation of the  
357 conversion of 2-phosphoglycerate to PEP through the enhanced biosynthesis of Eno2p (the glycolytic  
358 enzyme) and a decreased abundance of Eno1p (the gluconeogenic enzyme). A stimulation of the  
359 alcoholic fermentation in the hyperosmotic medium was obtained, as proved by the enhanced  
360 abundance of pyruvate decarboxylase and lower abundance of oxidative alcohol dehydrogenases. It  
361 is possible to hypothesize that alcoholic fermentation proceeds, even in a relatively lowered glycolytic  
362 flux, by exploiting also the pyruvate that comes from other paths.

363         Three fragments originating from Pdc1p (spot 1354A), Fba1p (1500A) and Eno1p (1507A)  
364 were found to be less abundant or totally lacking in a hyperosmotic medium. Since these fragments

365 are the result of a proteolytic action over the native protein, this finding suggests that proteolysis  
366 occurs to a lesser extent in high glucose conditions. As a support to this, the only proteolytic enzyme,  
367 Proteinase K (spot 1494A) was found in a lower abundance in the high-sugar medium grown cells.  
368 These results are in agreement with a recent report that suggests that the low expression of proteases  
369 in glucose-rich musts can cause fermentation arrests, due to the lack of nitrogen scavenger activity  
370 exerted by proteolytic enzymes (Szopinska et al., 2016). This is probably what also occurs for *S.*  
371 *cerevisiae* ISE 19.

372 Erasmus et al. (2003) reported an up-regulation of genes for glycolysis and for the pentose  
373 phosphate pathway, whereas genes involved in the *de novo* biosynthesis of purines, pyrimidines,  
374 histidine and lysine were down-regulated during hyperosmotic stress. These findings have also been  
375 confirmed at a proteomic level (Pham and Wright, 2002).

376 In the present work, no modifications have been observed in the biosynthetic pathway of  
377 histidine. However, the enzymes involved in amino acid biosynthesis displayed fold changes in the  
378 high glucose-grown cells. In fact, diaminopimelate epimerase (Yhi9p) (spots 1490A and 1493A), a  
379 piridoxalphosphate (PLP)-dependent isomerase involved in the so-called aspartate pathway leading  
380 to the synthesis of lysine, displayed a low abundance in the hyperosmotic medium, in agreement with  
381 the data reported above (Pham and Wright, 2002). On the contrary, two post-translationally different  
382 arginine-succinate synthases (Arg1p) (spot 1358B, pI 5.8 and spot 1577B pI 5.6) were more abundant  
383 (up to 10 fold) in the high sugar condition. Xu and co-workers (2011) demonstrated that arginine  
384 could protect the yeast *Candida glabrata* during hyperosmotic stress. Both imported (extracellular)  
385 arginine and *de novo* synthesized arginine lead to a higher biomass production (measured as dry cell  
386 weight). However, these authors also observed the enhanced transcription of genes encoding enzymes  
387 for arginine biosynthesis, thus suggesting that the second mechanism (*i.e. de novo* synthesis) is  
388 prevalent. Although a cryoprotective effect of arginine on the freezing stress of *S. cerevisiae* has been  
389 reported (Morita et al., 2002), the present proteomic results are the only ones that have found that

390 arginine is a good osmoprotectant in *S. cerevisiae* ISE19 as well as in *Candida glabrata*. Furthermore,  
391 our results support the observations of Gutierrez et al. (2012, 2015), who demonstrated that arginine  
392 exerted a positive effect (compared to other amino acids) on the growth and fermentation rate of *S.*  
393 *cerevisiae*. It is possible that arginine exerts this beneficial effect on growth not only because of its  
394 nutritional role as a nitrogen source, but also because of its osmoprotectant effect. On the other hand,  
395 arginine is one of the most abundant amino acid present in must (Gutierrez *et al.*, 2015), and it could  
396 have contributed to an evolutionary selection of *S. cerevisiae* strains in this ecological niche.

397         A glycosyltransferase, involved in the synthesis of cell-wall mannans (YJR075Wp-like  
398 protein) (spot 1688B), was only present in the high glucose concentration, thus suggesting the need  
399 of cell-wall processing and renewal during hyperosmotic stress. This is to be expected, since the cell-  
400 wall of *S. cerevisiae* is an elastic and dynamic structure responsive to changes in the external  
401 environment, which provides osmotic and physical protection to the yeast cell. Changes the cell-wall  
402 mannan structures under osmotic stress have been previously observed in yeasts (Koyama et al.  
403 2009). On the other hand, a unique oligosaccharide modification, mannosylphosphorylation, has been  
404 demonstrated in the cell-wall mannoproteins of *S. cerevisiae* during cellular response to a variety of  
405 stresses, among which osmotic stress, which strongly enhances mannosyl phosphorylation (Odani et  
406 al., 1997). These authors hypothesized that mannosylphosphate transfer, which gives a net negative  
407 charge to the cell-wall, allows the formation of a hydration shell on the cell surface, resulting in yeast  
408 cell protection from high solute stress. Whether this mechanism is also operative in *S. cerevisiae*  
409 ISE19 during osmotic stress still has to be elucidated.

410         An inverse correlation was found between osmotic stress and the abundance of oxidative-  
411 stress related enzymes, such as catalase T (Ctt1p) (spot 1326A and spot 1743A). Szopinska et al.  
412 (2016) have recently reported that the highest transcription rate of genes involved in antioxidant  
413 activities can be found when all the fermentable sugars have been depleted. The present findings are  
414 in agreement with these observations, and confirm that oxidative stress is a statistically rare event  
415 when sugars are abundant and hence not completely consumed.

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## CONCLUSIONS

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Alcoholic and glyceropyruvic fermentation are closely linked throughout winemaking. On average, 8% of must sugars undergoes glyceropyruvic fermentation, while the remaining part is converted to ethanol. The ability to produce glycerol varies according to the yeast strain, and can therefore affect the percentage of glycerol and ethanol formed by the same amount of fermented sugars. The present proteomic results on *S. cerevisiae* ISE 19 have not revealed any direct activation of the glyceropyruvic pathway at stationary phase after prolonged exposure to a hyperosmotic environment, in a condition leading to stuck fermentation, although the catalytic activation of the enzymes involved in glycerol synthesis cannot be excluded. On the other hand, an overall enhancement of the abundance of the proteins involved in alcoholic fermentation, cell-wall synthesis, aromatic amino acid as well as arginine biosynthesis has been detected. No apparent increase in abundance of stress proteins has been observed and proteolysis seems to be negatively modulated in hyperosmotic conditions.

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Understanding how osmotolerant yeasts are able to survive and adapt to critical conditions will allow a better biomass yield and an overall better alcoholic fermentation to be obtained. Moreover, the elucidation of the cytotoxic effects, induced by high glucose concentrations, could contribute to the optimization of the industrial fermentative yeast performance under hyperosmotic stress.

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440

## CONFLICTS OF INTEREST/ETHICAL CONCERNS

441 The authors declare that there are no conflicts of interest and no ethical issues (no animal or human  
442 involvement) in the experiments performed in the present investigation.

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## 589 CAPTIONS TO FIGURES

- 590 Figure 1. Fermentation performance, referring to ethanol production versus glucose consumption, in  
591 the ISE19 strain on Cortese grape must with regular (black line) and high (grey line) sugar contents.  
592 Error bars represent standard errors of the mean (n=3).
- 593 Figure 2. Growth kinetics of the ISE19 strain in Cortese grape must with regular (black line) and high  
594 (grey line) sugar contents. Error bars represent standard errors of the mean (n=3).
- 595 Figure 3. Acetate and glycerol production during fermentation by strain ISE19 in Cortese grape must  
596 with regular (black line) and high (grey line) sugar content. Error bars represent standard error of the  
597 mean (n=3).

598 Figure 4. Representative 2DE images of intracellular soluble proteins of *Saccharomyces cerevisiae*  
599 ISE 19 grown under a regular sugar condition (200 g/L) (on the left) and with the addition of  
600 supplementary sugar (260g/L) (on the right).

601 Figure 5. Schematic representation of the glyceropyruvic fermentation pathway.

602

603 **Tab.1. Protein identification.** B: proteins more abundant in the high glucose medium. A: proteins more abundant in the  
604 regular glucose medium

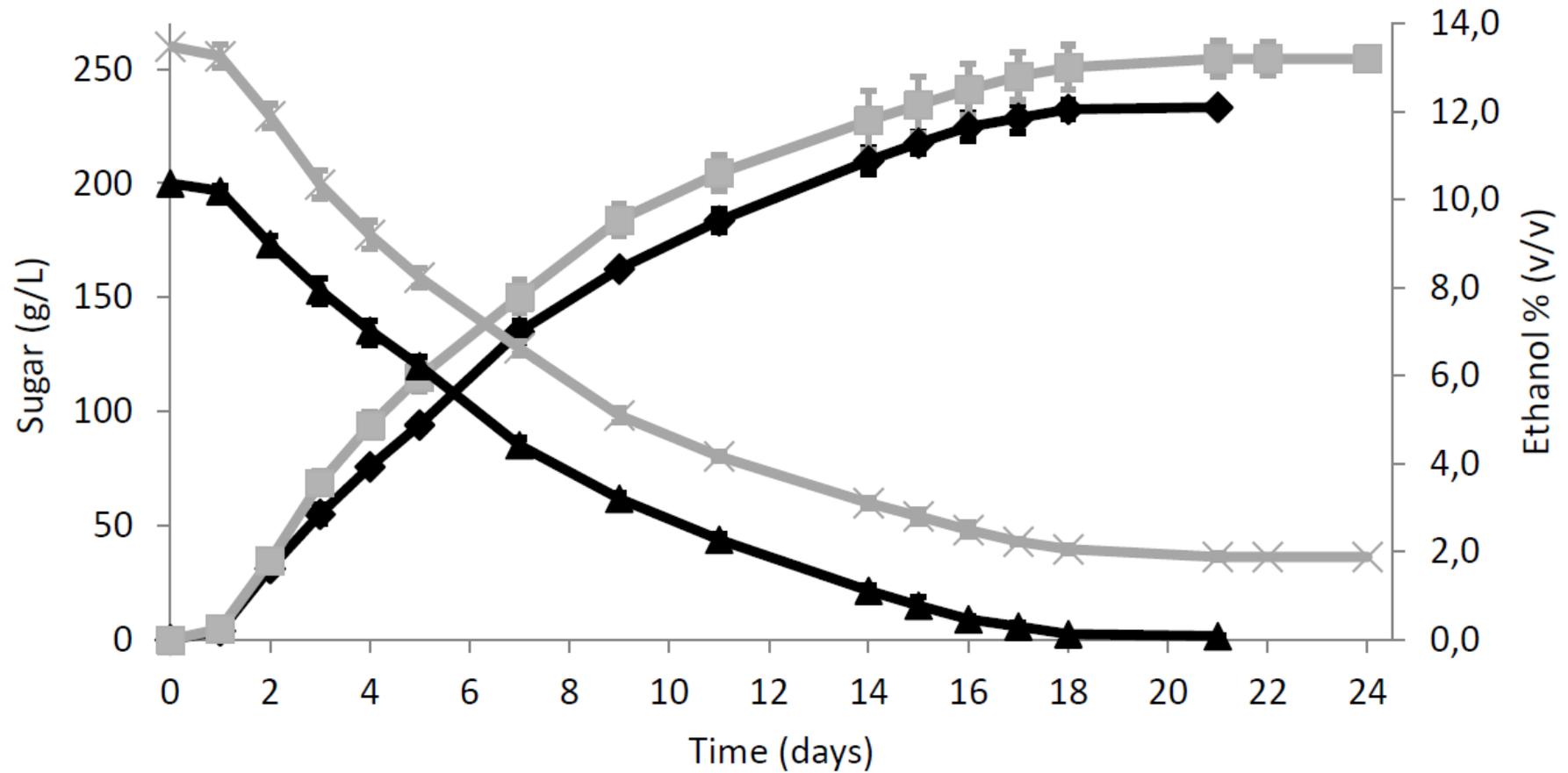
Spot n°	Fold changes	Name of the protein and acronym (if it exists )	Protein Entry (NCBI 2015.3.10)	Number of peptides/number of total signals	Sequence coverage by PMF	Molecular weight (Da) (Theoretical/experimental)	pI (Theoretical/experimental)
<b>1331B</b>	4	Pyruvate decarboxylase isozyme 1, Pdc1p	EGA57763	10/56	24%	61542/56000	5.8/6.1
<b>1358B</b>	2	Argininosuccinate synthase, Arg1p	EGA76938	14/51	36.6%	46455/47000	5.7/5.8
<b>1378B</b>	2.5	Phosphopyruvate hydratase, Eno2p	NP_012044	16/55	44.4%	46915/45000	5.7/6.2
<b>1415B</b>	3.5	Fructose-bisphosphate aldolase, Fba1p	EGA61531	12/58	43.5%	39607/40000	5.5/5.9
<b>1564B</b>	5	Pyruvate decarboxylase isozyme 1, Pdc1p	EGA57763	15/63	33%	61542/53000	5.8/5.8
<b>1569B</b>	2	Pyruvate decarboxylase isozyme 1, Pdc1p	EGA57763	18/74	41.7%	61496/58000	5.8/5.9
<b>1577B</b>	10	Argininosuccinate synthase, Arg1p	EGA76938	17/56	45.8%	46455/46500	5.7/5.6

<b>1663 B</b>	Only in B	phenylalanyl-tRNA synthetase beta subunit , Frs1p	AAT92797	9/25	20.3%	67332/70000	5.5/5.8
<b>1687 B</b>	Only in B	14-3-3 family protein, K7_Bmh2p	GAA22335	9/22	38.6%	30933/35000	4.8/4.5
<b>1688B</b>	Only in B	YJR075Wp-like protein	EDZ71169	4/33	11.7%	30721/32000	6.1/6.0
<b>1689B</b>	Only in B	14-3-3 family protein, K7_Bmh1p	GAA23007	13/30	47.9%	30205/35000	4.9/4.6
<b>1306A</b>	3	Methionine synthase, Met6p	EDN63067	27/58	39.4%	85831/85000	6.1/6.5
<b>1326A</b>	62	Catalase T, Ctt1p	AJP38866	9/76	21.4%	64560/64000	6.2/6.3
<b>1354A</b>	2.5	Pyruvate decarboxylase isozyme 1, Pdc1p (fragment)	EGA57763	12/54	24.7%	61496 /51000	5.8/5.9
<b>1396A</b>	2	Alcohol dehydrogenase, ADH1	AAA34410	10/35	31.3%	36823 /40000	6.3/6.5
<b>1400A</b>	2	Alcohol dehydrogenase, ADH1	AAA34410	9/61	24.4%	36823/40000	6.3/6.3
<b>1419A</b>	4	Alcohol dehydrogenase, ADH1	AAA34410	6/41	18%	36837/40000	5.9/5.6
<b>1434A</b>	25	Enolase, Eno1p	EGA82740	11/27	40.1%	41709/38000	6.2/6.5
<b>1485A</b>	Only in A	S-adenosylmethionine synthetase, Sam1p	EGA73728	5/49	29.5%	28481/33000	6.0/6.0
<b>1490A</b>	Only in A	Diaminopimelate epimerase, Yhi9p	EGA58492	7/32	31.6%	32186/31000	5.5/6.2

		Ssf2p	EGA83416	4/32	18.2%	32878/31000	6.2/6.2
<b>1493A</b>	8.5	Inorganic pyrophosphatase, Ipp1p	AJP83924	8/43	37.3%	32284/31000	5.4/5.8
		Diaminopimelate epimerase, Yhi9p	EGA58492	5/43	24.7%	32186/31000	5.5/5.8
<b>1494A</b>	2.5	Peptidases_S8_PCSK9_ProteinaseK_like (from YEL060Cp-like protein aa 130-406)	EDZ72718	6/34	12.8%	29297/31000	6.8/6.6
<b>1500A</b>	3.5	Fructose-bisphosphate aldolase, Fba1p fragment (starting from aa 1)	EGA61531	7/42	20.3%	39607/30000	5.5/5.5
<b>1507A</b>	Only in A	Enolase, Eno1p fragment (starting from aa 116)	EGA82740	7/50	20%	29715/30000	5.3/5.1
<b>1513A</b>	5	YAL034W-Ap-like protein	EDZ74019	6/42	32.9%	29537/28000	6.1/5.8
<b>1515A</b>	2	Triose-phosphate isomerase, Tpi1p	EGA87556	3/39	18.3%	27305/27000	6.3/6.3
<b>1519A</b>	2	Triose-phosphate isomerase, Tpi1	NP_010335	10/48	49.2%	26796/27000	5.7/5.9
<b>1743A</b>	5.5	Catalase T, Ctt1p	EDV10159	13/44	27.4%	65696/63000	6.2/6.6

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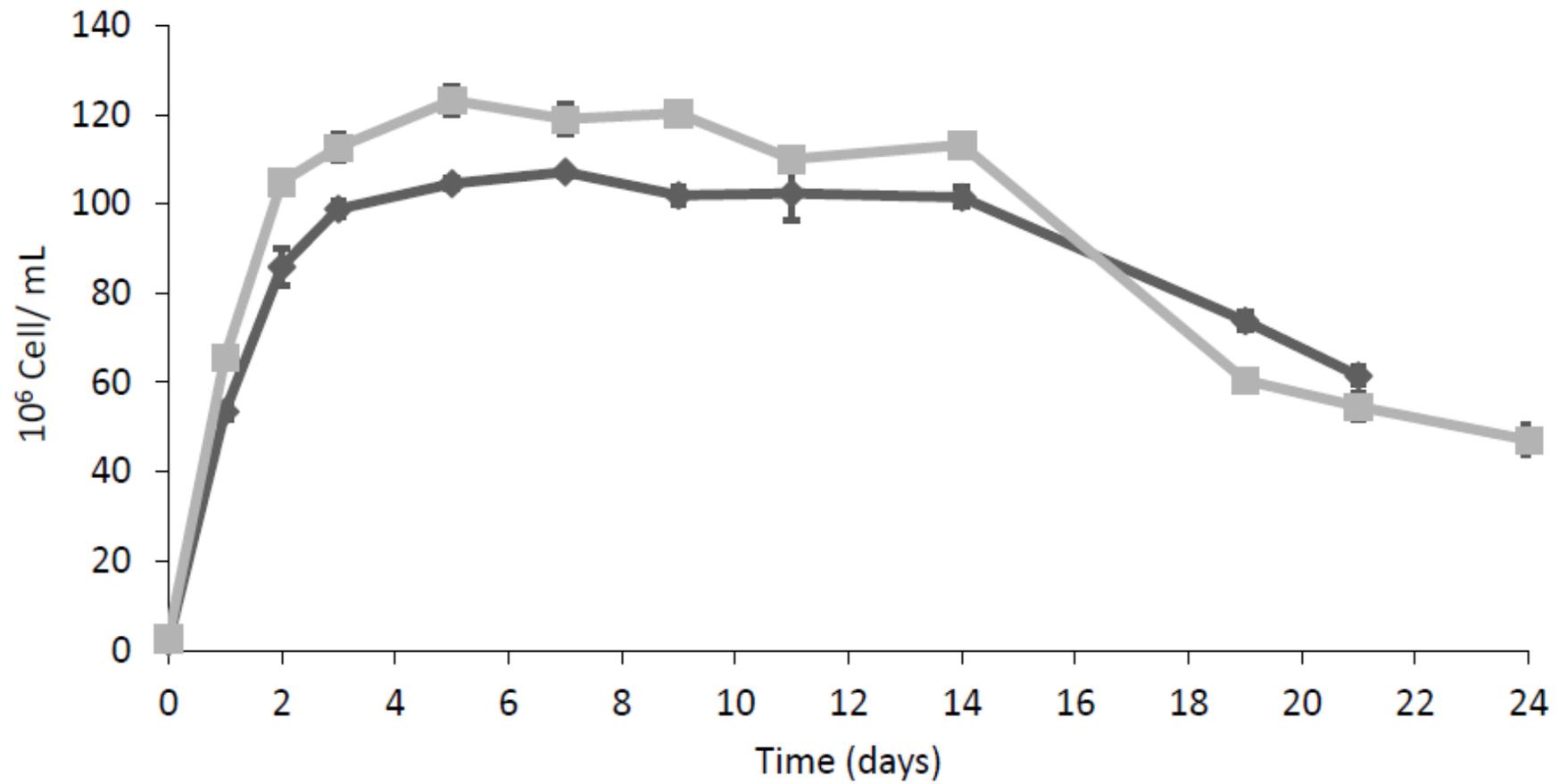
607 Fig. 1



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609 Fig, 2

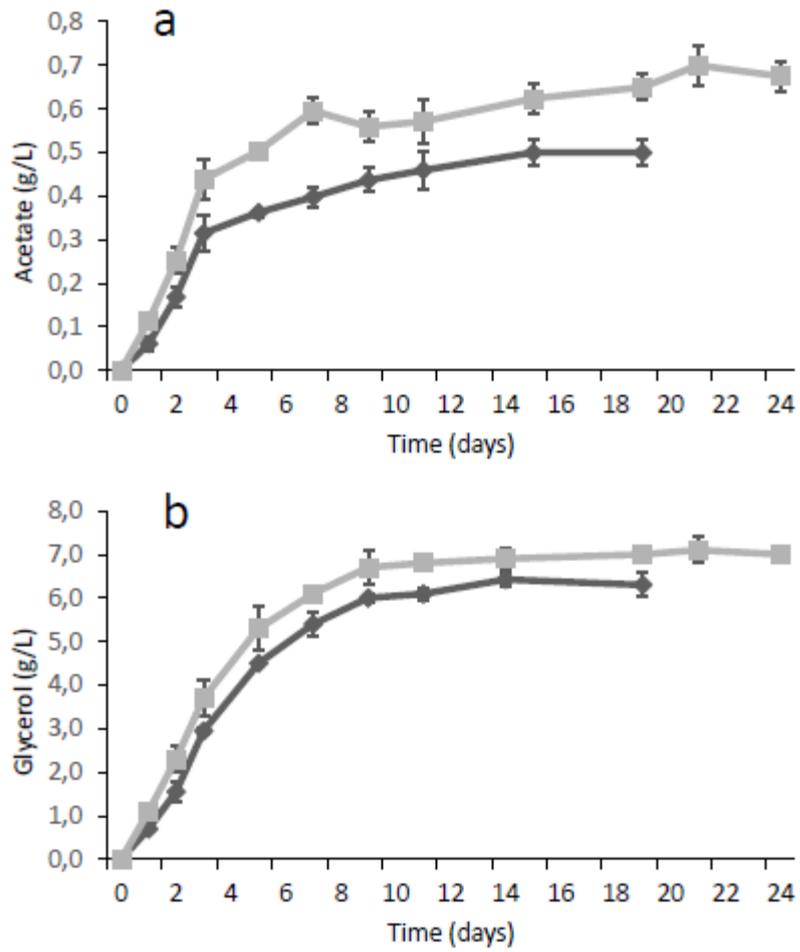
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613 Fig. 3



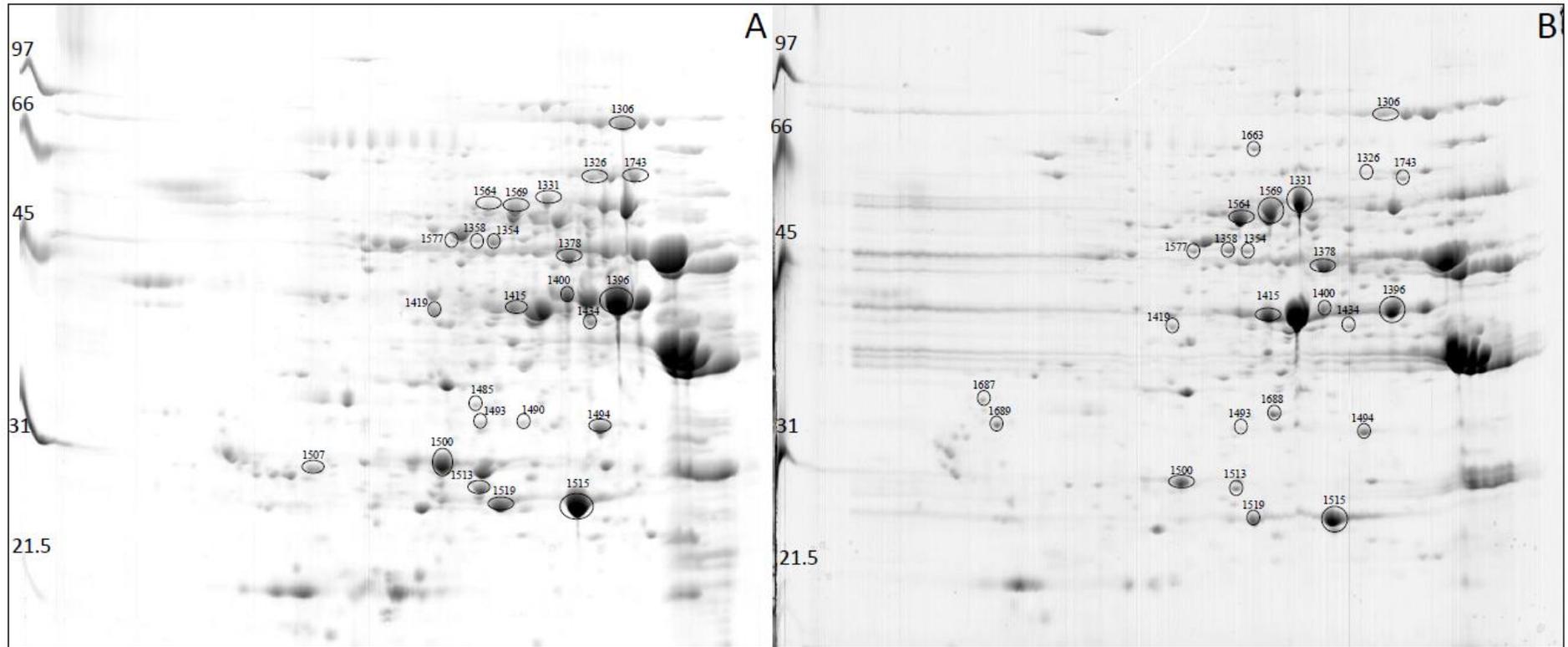
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617 Fig. 4

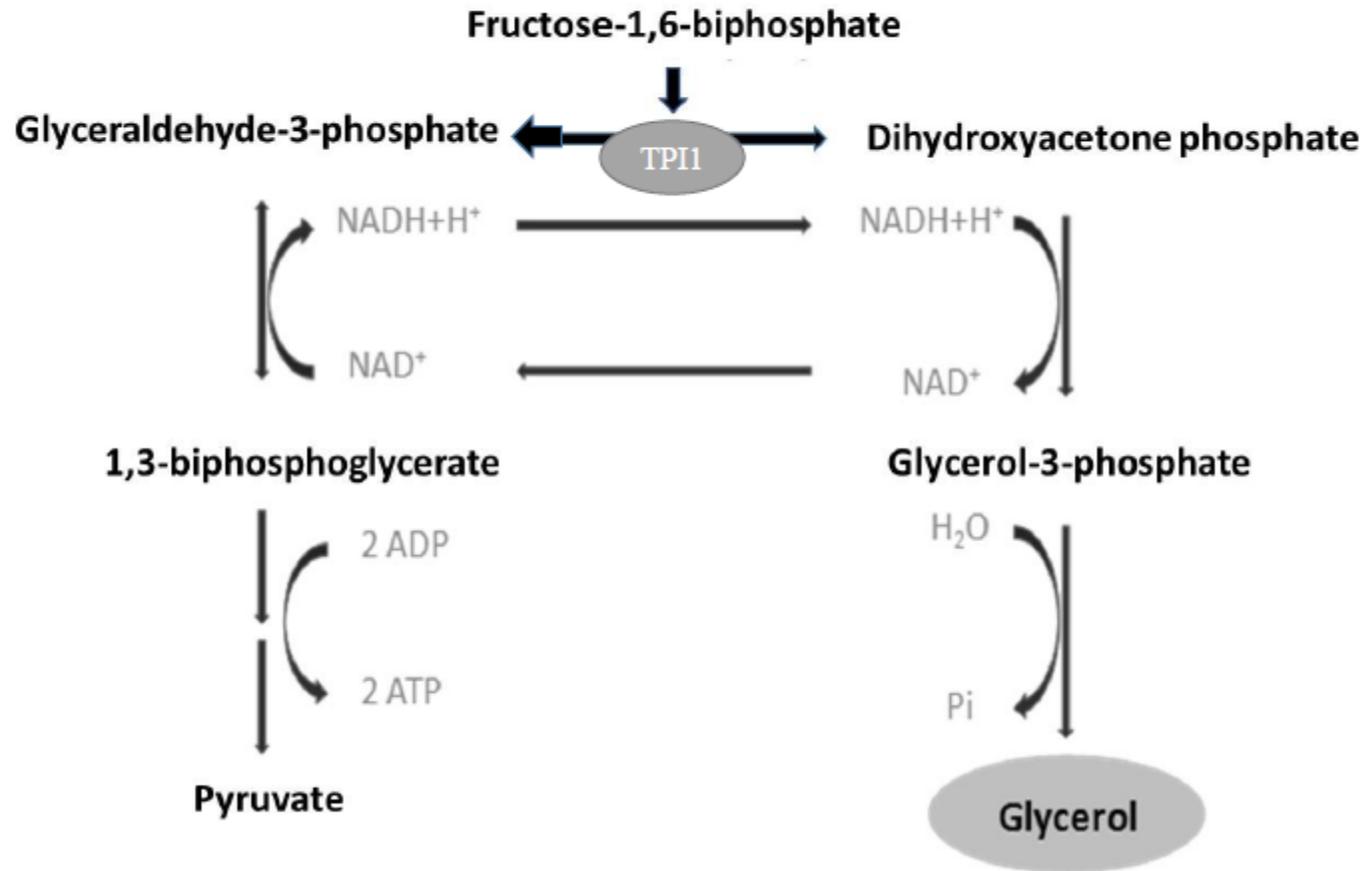
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# GLYCEROPYRUVIC FERMENTATION



623

## HIGHLIGHTS

- 624
- The paper describes what happens at a proteomic level when *S. cerevisiae* ISE19 is grown in  
625 high sugar grape musts in a condition leading to a fermentation arrest.
  - A decreased abundance of proteolytic enzymes and enzyme fragments was observed in a high  
626 sugar condition, in agreement with recent literature data that have reported how the low  
627 expression of proteases in glucose-rich musts can cause the arrest of alcoholic fermentation.  
628
  - An increased abundance of cell-wall renewal enzymes and of the proteins that regulate  
629 membrane transport underline an effective stress response concerning envelope structures.  
630
  - Apart from proline, arginine could also play a direct protective role against osmotic stress in  
631 *S. cerevisiae* ISE19 (as previously demonstrated for cold stress), since its biosynthetic  
632 pathway seems to be activated.  
633

634

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