

Fluidization of Membrane Lipids Enhances the Tolerance of *Saccharomyces cerevisiae* to Freezing and Salt Stress[∇]

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Unsaturated fatty acids play an essential role in the biophysical characteristics of cell membranes and determine the proper function of membrane-attached proteins. Thus, the ability of cells to alter the degree of unsaturation in their membranes is an important factor in cellular acclimatization to environmental conditions. Many eukaryotic organisms can synthesize dienoic fatty acids, but *Saccharomyces cerevisiae* can introduce only a single double bond at the Δ^9 position. We expressed two sunflower (*Helianthus annuus*) oleate Δ^{12} desaturases encoded by *FAD2-1* and *FAD2-3* in yeast cells of the wild-type W303-1A strain (*trp1*) and analyzed their effects on growth and stress tolerance. Production of the heterologous desaturases increased the content of dienoic fatty acids, especially 18:2 $\Delta^{9,12}$, the unsaturation index, and the fluidity of the yeast membrane. The total fatty acid content remained constant, and the level of monounsaturated fatty acids decreased. Growth at 15°C was reduced in the *FAD2* strains, probably due to tryptophan auxotrophy, since the *trp1* (*TRP1*) transformants that produced the sunflower desaturases grew as well as the control strain did. Our results suggest that changes in the fluidity of the lipid bilayer affect tryptophan uptake and/or the correct targeting of tryptophan transporters. The expression of the sunflower desaturases, in either *Trp*⁺ or *Trp*⁻ strains, increased NaCl tolerance. Production of dienoic fatty acids increased the tolerance to freezing of wild-type cells preincubated at 30°C or 15°C. Thus, membrane fluidity is an essential determinant of stress resistance in *S. cerevisiae*, and engineering of membrane lipids has the potential to be a useful tool of increasing the tolerance to freezing in industrial strains.

Tolerance to freezing is an essential trait influencing the viability and leavening capacity of baker's yeast in frozen dough (4, 42). The so-called frozen-dough technology has been widely accepted by consumers and bakers due to several advantages, which include supplying oven-fresh bakery products and improving labor conditions. However, no appropriate industrial strain with a high tolerance to freezing is available, and it is unlikely that the classical breeding program could significantly improve this trait. Freezing is a complex and multifaceted stress, in which different stressors and stress responses appear to play important roles. Cells exposed to subzero temperatures are injured by the formation of ice crystals and crystal growth during frozen storage (33). At a slow freezing rate, cells are exposed to hyperosmotic solutions and equilibrate by movement of water across the membranes (65). Finally, during the thawing process, cells can suffer biochemical damage by oxidative stress (16). It is not surprising, therefore, that tolerance to freezing involves several mechanisms working in concert.

Biological membranes are the first barrier that separates cells from their environment and are a primary target for damage during environmental stress. Sudden changes in envi-

ronmental conditions cause alterations in the organization and dynamic structure of membrane lipids (62) and alter the function of many cellular activities. For example, reduced incubation temperatures increase the molecular order of membrane lipids, i.e., rigidification (29), and alter the activity of membrane-associated enzymes and transporters (5). Other stresses, e.g., heat shock, freezing, and osmotic stress, induce dramatic changes in the organization and dynamic properties of membrane lipids (12, 27). To date, most of the research in this field has focused on the connections between the physical state of the membrane and cold tolerance.

Many organisms have developed mechanisms to maintain the appropriate fluidity of membrane lipids regardless of ambient temperature. These mechanisms include changes in the proportions of types of lipid and alterations in the lipid/protein ratio (26). The most widely recognized change in cell membranes at low temperatures is the unsaturation of lipid acyl chains (44, 54). Phospholipids with unsaturated fatty acids have a lower melting point and more flexibility than do phospholipids with saturated acyl chains (35). Such adaptation involves the induction of fatty acid desaturases (55, 63), which incorporate unsaturated bonds at defined positions in fatty acids that are linked to membrane glycerolipids.

In *Saccharomyces cerevisiae*, exposure to low temperature increases the expression of *OLE1* (36), which encodes the only known desaturase in this yeast (52, 53). Ole1p, a Δ^9 fatty acid desaturase, converts palmitic (16:0) and stearic (18:0) fatty acids into their corresponding monounsaturated fatty acids, palmitoleic acid (16:1 Δ^9) and oleic acid (18:1 Δ^9), respectively.

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Consistent with the increased expression of *OLE1*, there is an increase in the degree of unsaturation of total fatty acids when yeast cells are shifted from 30°C to 10°C (36). Nevertheless, *OLE1* does not appear to be essential in acclimation to low temperature, since its overexpression does not confer growth advantages at 10°C (20). Overexpression of *OLE1* is toxic and reduces growth at 30°C (52). Thus, the functional role of *OLE1* is unclear, and the mechanism by which *S. cerevisiae* alters membrane fluidity in response to different types of stress remains unknown.

Unlike *S. cerevisiae*, many organisms synthesize polyunsaturated fatty acids *de novo* through the activity of specific desaturase enzymes. Genes encoding a range of different fatty acid desaturases (*FAD*) have been cloned from microorganisms, animals, and plants, and expressed in heterologous hosts (28, 37, 38), including *S. cerevisiae* (14, 19, 40, 43). *FAD2*-expressing yeast cells contained high levels of diunsaturated fatty acids. However, the physiological significance of this change in fatty acid composition has only rarely been studied in detail. *S. cerevisiae* cells overexpressing the *Arabidopsis FAD2* gene were more resistant to ethanol than were control cells (19). Production of a Δ^{12} desaturase from *Caenorhabditis elegans* in yeast increased the growth rate at low temperatures and enhanced resistance to ethanol and H₂O₂ (40).

Cultivated sunflower (*Helianthus annuus* L.) seeds are rich in unsaturated fatty acids 18:1 Δ^9 and 18:2 $\Delta^{9,12}$ (linoleic acid). The enzyme responsible for synthesizing linoleic acid is the microsomal oleate desaturase (1-acyl-2-oleoyl-*sn*-glycero-3-phosphocholine Δ^{12} desaturase). Three different cDNA sequences, *FAD2-1*, *FAD2-2*, and *FAD2-3*, encoding the sunflower microsomal oleate desaturases (fatty acid desaturase 2 [FAD2]) have been isolated and characterized (31). *FAD2* activity in developing sunflower seeds is regulated by temperature and oxygen availability (32). *FAD2* activity levels were similar at 10°C and 20°C and decreased at 30°C, which is consistent with a hypothesis that *FAD2* activity is decreased by high temperatures. This phenomenon has been mainly attributed to the relatively low thermal stability of the major and seed-specific desaturase isoform *FAD2-1* (45).

Our objective in this study was to alter the unsaturation index of the *S. cerevisiae* membrane through the heterologous expression of the sunflower desaturase genes, *FAD2-1* and *FAD2-3*. We hypothesized that gene-engineered fluidization of the membrane lipids might play a protective role upon freezing. The results may have practical applications in increasing yeast resistance to freezing.

MATERIALS AND METHODS

Strains, culture media, and general methods. *S. cerevisiae* W303-1A (*MAT α leu2-3,112 ura3-1 trp1-1 his3-11,15 ade2-1 can1-100 GAL mal SUC2*) wild-type strain (57) was used throughout this work. *Escherichia coli* strain DH10B was used as the host for plasmid construction. Yeast cells were cultured at 30°C in YPD (1% yeast extract, 2% peptone, 2% glucose) or SD [0.2% yeast nitrogen base without amino acids (DIFCO, BD Diagnostics, Sparks, MD), 0.5% (NH₄)₂SO₄, 2% glucose] supplemented with the appropriate auxotrophic requirements (49). In some experiments, the concentration of tryptophan was increased by supplementing the medium with 200 μ g/ml of this amino acid. *E. coli* was grown in Luria-Bertani (LB) medium (1% peptone, 0.5% yeast extract, 0.5% NaCl) supplemented with ampicillin (50 mg/liter). Yeast cells were transformed by the lithium acetate method (18). *E. coli* was transformed by using an Eppendorf electroporator 2510 (Eppendorf AG, Hamburg, Germany).

Stress sensitivity tests. Cells were grown at 30°C to midexponential phase, collected by centrifugation (3,000 \times g, 2 min, 4°C), transferred to fresh medium, and incubated at various temperatures, after which growth was monitored. Doubling times (*g*) were calculated from the formula $g = \ln 2/\mu$, where μ is the specific growth rate constant of the culture. μ was calculated from the slope of the line obtained after plotting $\ln X$ versus *t*, where *X* is the cell density of the culture, measured as optical density at 600 nm (OD₆₀₀), at multiple time points (*t*) during logarithmic growth. For plate phenotype experiments, cultures were diluted to an OD₆₀₀ of 0.3, and 10-fold serial dilutions were spotted (3 μ l) onto SD or YPD agar solid medium containing sorbitol or NaCl at different concentrations. Unless otherwise indicated, colony growth was inspected after 2 to 4 days of incubation at 30°C.

For freezing tolerance assays, cells were grown in SD medium at 30°C or 15°C, harvested (OD₆₀₀ of 3), and resuspended in YPD (OD₆₀₀ of 10), and 10- μ l aliquots were shifted to -20°C. At various times, samples were thawed at 30°C for 10 min and diluted, and cells were plated onto solid YPD. After 2 days at 30°C, colonies were counted. Viability is expressed as the percentage of viable cells relative to unfrozen control samples.

Plasmids. Plasmids for expressing *FAD2* desaturases were pVTHaFAD2-1 and pVTHaFAD2-3 (45), which contain the sunflower (*H. annuus*) genes *FAD2-1* (GenBank accession number AF251842) and *FAD2-3* (GenBank accession number AF251844), respectively, flanked by the *S. cerevisiae ADHI* promoter in the *URA3*-based multicopy vector pVT102-U (60).

Northern blot. Total RNA was prepared as previously described (49). Equal amounts of RNA (10 μ g) were separated in 1% (wt/vol) agarose gels containing formaldehyde (2.5% vol/vol), transferred to a nylon membrane, and hybridized with a ³²P-labeled probe of the *FAD2-1* and *FAD2-3* genes. Probes were obtained by restriction with BamHI of plasmids pVTHaFAD2-1 and pVTHaFAD2-3. A PCR-generated fragment of the *S. cerevisiae ACT1* gene (+10 to +1,066) was used as the loading control. Probes were radiolabeled with the random primer Ready-to-Go kit (Amersham Biosciences, Chalfont-St. Giles, England) and [α -³²P]dCTP (Amersham Biosciences). Hybridization was carried out under standard conditions (49). Filters were exposed to a high-resolution BAS-MP 2040S imaging plate (Fuji, Kyoto, Japan) for 24 h and scanned in a phosphor-imager (FLA-3000; Fuji).

Lipid analysis. Cells were grown to stationary phase (OD₆₀₀ of ~3) in SD at 30°C or 15°C. Culture samples of 50 ml corresponding to approximately 45 mg (dry weight) of cells (OD₆₀₀ of 1 equals 0.3 mg [dry weight] of cells/ml) were centrifuged (3,000 \times g, 2 min, 4°C) and washed twice with ultrapure water (MilliQ RO 10 Plus; Millipore, Bedford, MA). Total lipid content and fatty acid composition of whole yeast cells were determined by using the one-step method of Garcés and Mancha (15). Briefly, following the addition of 3.3 ml methanol-toluene-dimethoxypropane-H₂SO₄ (39:20:5:2, vol/vol/vol/vol) and 1.7 ml heptane to the yeast pellet, the mixture was incubated at 80°C for 1 h, forming a single phase. After the mixture was cooled, the upper phase containing the fatty acid methyl esters was separated, washed with 5 ml 6.7% Na₂SO₄, and evaporated to dryness under nitrogen. The methyl esters were dissolved in an appropriate volume of heptane and analyzed by gas-liquid chromatography using a HP-5890 (Hewlett-Packard, Palo Alto, CA) fitted with a capillary column (30-m length; 0.25-mm inner diameter; 0.20- μ m film thickness) of fused silica (Supelco, Bellefonte, PA) and a flame ionization detector. Hydrogen was used as the carrier gas with a linear rate of 28 cm s⁻¹ and a split ratio of 1/50. The temperature of the injector and detector was 220°C, and the oven temperature was 170°C. Heptadecanoic acid was used as an internal standard.

The yeast lipid composition was determined from yeast cells harvested and washed as described above. After the cell pellet was heated at 100°C for 10 min to stop any enzymatic reaction, the fresh weight of the cell pellet was measured, and the yeast cells were resuspended with distilled water. Lipids were extracted from 1-ml aliquots with 3.75 ml of chloroform-methanol (1:2, vol/vol) according to the method of Bligh and Dyer (9) with the modifications of Kates (24), and the lower phase was separated and evaporated to dryness with nitrogen. Fatty acid composition of the different lipid classes was determined as described previously (45).

Membrane fluidity determination. Membrane fluidity was measured as previously described (27) by using the fluorescent probe 1,6-diphenyl-1,3,5-hexatriene as a reporter. The degree of fluorescence polarization was calculated as described by Ansari et al. (3). In these experiments, decreases in the degree of fluorescence polarization reflect increases of the fluidity of the lipid bilayer, which controls or affects the mobility of DHP on the membrane.

Statistical analysis. The significance of variations in the unsaturation index among strains was determined by a global analysis of variance (available at www.physics.csbsju.edu/stats/anova.html).

TABLE 1. Fatty acid composition of total lipids in *S. cerevisiae* *FAD2* transformants grown at different temperatures^a

Strain	Temp (°C)	Fatty acid composition (mol%) ^b						UI ^c	Total wt of fatty acids ^d
		16:0	16:1	16:2	18:0	18:1	18:2		
<i>trp1</i> strains									
W303-1A	30	20 ± 0.5	34 ± 1.2	UD ^e	11 ± 0.3	36 ± 1.4	UD	0.69 A	21
	15	20 ± 0.1	35 ± 0.7	UD	8.9 ± 0.2	37 ± 0.6	UD	0.71 A	22
W303FAD2-1	30	20 ± 0.4	30 ± 1.4	1.6 ± 0.4	11 ± 1.7	29 ± 0.6	8.0 ± 0.1	0.79 B	18
	15	20 ± 1.3	23 ± 1.1	6.0 ± 0.3	12 ± 0.9	18 ± 0.2	20 ± 2.8	0.94 C	26
W303FAD2-3	30	22 ± 0.8	27 ± 0.8	5.2 ± 0.0	12 ± 1.1	16 ± 0.4	19 ± 1.0	0.90 C	20
	15	20 ± 0.2	27 ± 0.5	5.1 ± 0.1	11 ± 0.1	15 ± 0.2	22 ± 0.6	0.97 C	26
<i>trp1 TRP1</i> strains									
W303-1A	30	21 ± 0.5	31 ± 0.5	UD	11 ± 1.6	37 ± 1.4	UD	0.68 A	39
	15	19 ± 0.9	39 ± 0.4	UD	9.5 ± 1.4	33 ± 0.4	UD	0.72 AB	49
W303FAD2-1	30	20 ± 0.9	30 ± 0.9	UD	11 ± 0.7	33 ± 0.5	6.0 ± 0.9	0.74 B	36
	15	19 ± 0.3	27 ± 0.6	7.2 ± 1.2	11 ± 0.2	16 ± 1.9	20 ± 1.2	0.97 C	45
W303FAD2-3	30	22 ± 0.9	23 ± 2.8	5.4 ± 1.7	12 ± 0.8	16 ± 3.3	21 ± 2.7	0.92 C	34
	15	19 ± 0.5	27 ± 2.0	6.6 ± 1.3	11 ± 1.9	16 ± 3.5	20 ± 1.5	0.96 C	48

^a Tryptophan auxotrophic (*trp1*) and prototrophic (*trp1 TRP1*) cells of the *S. cerevisiae* W303-1A wild-type strain expressing the sunflower genes *FAD2-1* and *FAD2-3* were analyzed.

^b Values are the means ± standard errors of the means for at least three independent experiments with duplicate determinations of fatty acid composition.

^c UI, unsaturation index. The unsaturation index was defined as follows: [(percentage of 16:1 + percentage of 18:1) + 2(percentage of 16:2 + percentage of 18:2)]/100. Values with different letters are significantly different at a *P* of 0.01 (analysis of variance).

^d In micrograms per milligram of cells (dry weight).

^e UD, undetected.

RESULTS

Heterologous expression of sunflower *FAD2* desaturases enhances unsaturation of yeast lipids. *S. cerevisiae* W303FAD2-1 and W303FAD2-3 strains, which express the sunflower genes *FAD2-1* and *FAD2-3*, respectively, were analyzed for *FAD2* mRNA levels. Northern blot analysis showed a single hybridizing band that was absent in samples of the control strain transformed with an empty plasmid (data not shown). Differences in the expression levels of *FAD2-1* and *FAD2-3* were insignificant in cells growing either actively or in the diauxic shift. Moreover, none of the transformant strains had abnormal-sized desaturase mRNAs (data not shown).

Heterologous expression of microsomal oleate desaturase-encoding genes resulted in the production of palmitolinoleic (16:2Δ^{9,12}) and linoleic acid (18:2Δ^{9,12}), and the reduction of the amount of fatty acids 16:1Δ⁹ and 18:1Δ⁹, thus altering the fatty acid profile and increasing the unsaturation index of yeast lipids (Table 1). This result indicates that the sunflower desaturases are active and act on endogenous yeast monounsaturated fatty acids, preferentially converting oleic acid to linoleic acid (Table 1). As in a previous study (45), the dienoic acids were almost evenly distributed among the different lipid classes analyzed, including polar (phosphatidylcholine, phosphatidylethanolamine, phosphatidylserine, and phosphatidylinositol) and neutral lipids (diacylglycerol, triacylglycerol, and sterol ester), although a higher percentage was detected in phosphatidylethanolamine and neutral lipids, two of the most prominent components of the yeast plasma membrane lipids (8). As previously reported (32, 45), the incubation temperature altered the amount of unsaturated fatty acids present and the monoenoic/dienoic acid ratio of the transformed cells. Cells incubated at 15°C contained higher levels of dienoic acids

than did those cultivated at 30°C (Table 1). This difference was statistically significant (*P* < 0.01) in cells expressing the *FAD2-1* gene, in which the percentages of 16:2 and 18:2 fatty acids increased four- and threefold, respectively, at 15°C relative to levels at 30°C. However, the activity of *FAD2* desaturases did not alter the total amount of fatty acids, except at 15°C, where a moderate increase was observed (Table 1).

Effects of heterologous *FAD2* desaturases on membrane fluidity and growth. Membrane fluidity in whole cells of wild-type and *FAD2*-overexpressing strains was estimated by measuring the fluorescence polarization of the lipophilic membrane probe 1,6-diphenyl-1,3,5-hexatriene. In both strains expressing *FAD2*, W303FAD2-1 and W303FAD2-3, the fluorescence polarization values at 25°C were significantly lower, 0.116 ± 0.033 and 0.125 ± 0.020, respectively, than those of the control cells (0.160 ± 0.016). Thus, the fluidity of yeast membrane lipids increases when monoenoic fatty acids are converted to dienoic fatty acids.

Overproduction of *FAD2* desaturases increased growth at 30°C and decreased growth of wild-type cells cultivated in liquid SD medium at 10 or 15°C (Table 2), with *FAD2*-overproducing cells not producing visible colonies on solid YPD at 15°C (Fig. 1A). Similar phenotypes were observed when cells were plated on solid media, both SD (data not shown) and YPD (Fig. 1A), but the effect of *FAD2* on growth at low temperature was more pronounced.

Nutrient uptake may be sensitive to changes in the fatty acid composition of the yeast membrane. Tryptophan uptake can affect the growth temperature profile of *S. cerevisiae* (1) and is impaired in cells exposed to low temperatures (1), and the strain used in this study was a *trp1* strain. Yeast growth was stimulated by increasing tryptophan availability at low temper-

TABLE 2. Growth of *FAD2* transformants at different temperatures^a

Strain	Doubling time (h) at ^b :		
	30°C	15°C	10°C
W303-1A	2.2 ± 0.1	11.5 ± 0.2	89 ± 5.3
W303FAD2-1	1.7 ± 0.1	13.3 ± 0.2	107 ± 5.2
W303FAD2-3	1.7 ± 0.1	12.8 ± 0.1	107.3 ± 12

^a Tryptophan auxotrophic (*trp1*) cells of the *S. cerevisiae* W303-1A wild-type strain expressing the sunflower genes *FAD2-1* and *FAD2-3* were analyzed. Cells were grown in liquid SD medium.

^b Values represent the means ± standard errors of the means for at least two independent experiments.

atures (Fig. 1A), although the growth reduction was still detectable under these conditions. The addition of excess tryptophan did not affect yeast cell growth at 30°C. No growth differences at either 15 or 30°C were observed between wild-type and *FAD2*-overexpressing strains transformed with the integrative plasmid YIplac112, carrying the wild-type *TRP1* gene (Fig. 1A). This result was not due to a lack of activity of the heterologous desaturases in the Trp⁺ background, since both *S. cerevisiae* W303FAD2-1 and W303FAD2-3 accumulated dienoic fatty acids (Table 1) in a manner similar to that observed in the corresponding tryptophan auxotrophic strains (Table 1).

Membrane fluidity and tolerance to ion stress and freezing injury. Production of dienoic fatty acids did not alter the growth of yeast cells, either Trp⁺ or Trp⁻, exposed to different concentrations of sorbitol (data not shown). However, overexpression of *FAD2* genes did increase Na⁺ tolerance relative to strains harboring an empty plasmid (Fig. 1B).

Cultures of wild-type and *FAD2*-expressing cells were transferred from 30 to -20°C and analyzed for cell viability after different periods of frozen storage. The viability of wild-type W303-1A (*trp1*) cells, in which no detectable dienoic fatty acids were produced, was less than that of Trp⁻ transformed cells carrying a high-copy-number expression cassette of *FAD2* (Fig. 2). The extent of unsaturation of lipids at 30°C was critical for cell survival below 0°C. Cells expressing *FAD2-1* died more rapidly when frozen than did the cells producing the *FAD2-3* enzyme, which corresponds with their dienoic acid content (Table 1). Similar results were also observed for the Trp⁺ strains, although the effects on tolerance to freezing were less pronounced (Fig. 2).

Yeast cell survival following freezing and frozen storage increased if the cells were grown at 15°C instead of 30°C (Fig. 2), confirming that death during freezing can be prevented or alleviated by growth at low temperatures (23, 39). Again, the loss of viability following freezing was significantly larger for the control strain. In a representative experiment, ~50% of wild-type cells and ~90% of the *FAD2-3*-overproducing cells survived for 35 days at -20°C (Fig. 2). The differences in tolerance to freezing of *FAD2-3* and *FAD2-1*-producing cells grown at 15°C were less evident than those observed in cells grown at 30°C, probably because the two *FAD2*-expressing strains produce similar amounts of dienoic fatty acids at low temperatures (Table 1). These observations were further confirmed in Trp⁺ strains (Fig. 2).

DISCUSSION

Heterologous expression of sunflower microsomal oleate desaturases in yeast cells enabled us to evaluate the functional role of dienoic fatty acids. Cells of *S. cerevisiae* into which either the *FAD2-1* or *FAD2-3* gene for Δ^{12} desaturases from *H. annuus* were introduced could efficiently convert palmitoleic and oleic acid into palmitolinoleic and linoleic acid, respectively. The extent of accumulation of dienoic acids was similar

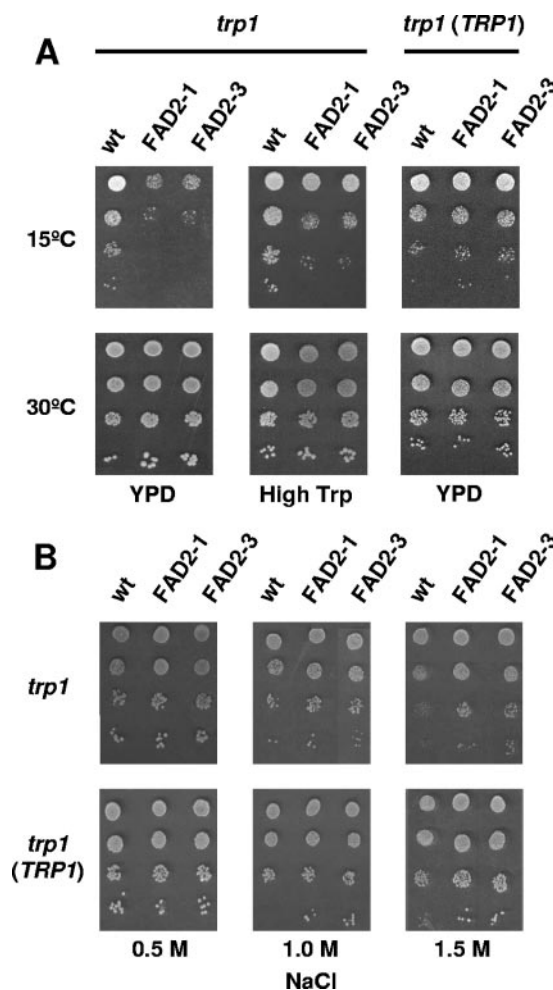


FIG. 1. *FAD2*-overexpressing yeast cells display *trp1*-dependent cold sensitivity and enhanced NaCl tolerance. (A) Tryptophan auxotrophic (*trp1*) cells of the *S. cerevisiae* W303-1A wild-type strain (wt) were transformed with plasmids pVTHaFAD2-1 (*FAD2-1*) and pVTHaFAD2-3 (*FAD2-3*), which contain the sunflower (*H. annuus*) genes *FAD2-1* and *FAD2-3*, respectively, and transformants were assayed for growth at 15°C and 30°C. Wild-type and *FAD2*-overexpressing strains transformed with the integrative plasmid YIplac112, carrying the wild-type *TRP1* gene (*trp1 TRP1*), were also tested. Cells were grown in SD liquid medium at 30°C until early exponential phase and adjusted to an OD₆₀₀ of 0.3. Serial 10-fold dilutions (to 10⁻³) of the adjusted cultures were spotted (3 μ l) onto standard YPD agar plates (YPD) or YPD plates containing excess tryptophan (200 μ g per ml) (High Trp). Plates were incubated for 2 (30°C) or 7 (15°C) days. (B) The same strains were cultivated at 30°C on YPD plates containing NaCl at the indicated concentrations and inspected after 5 days. Cultures were pregrown and diluted, and cells were spotted as described above. In all cases, a representative experiment is shown.

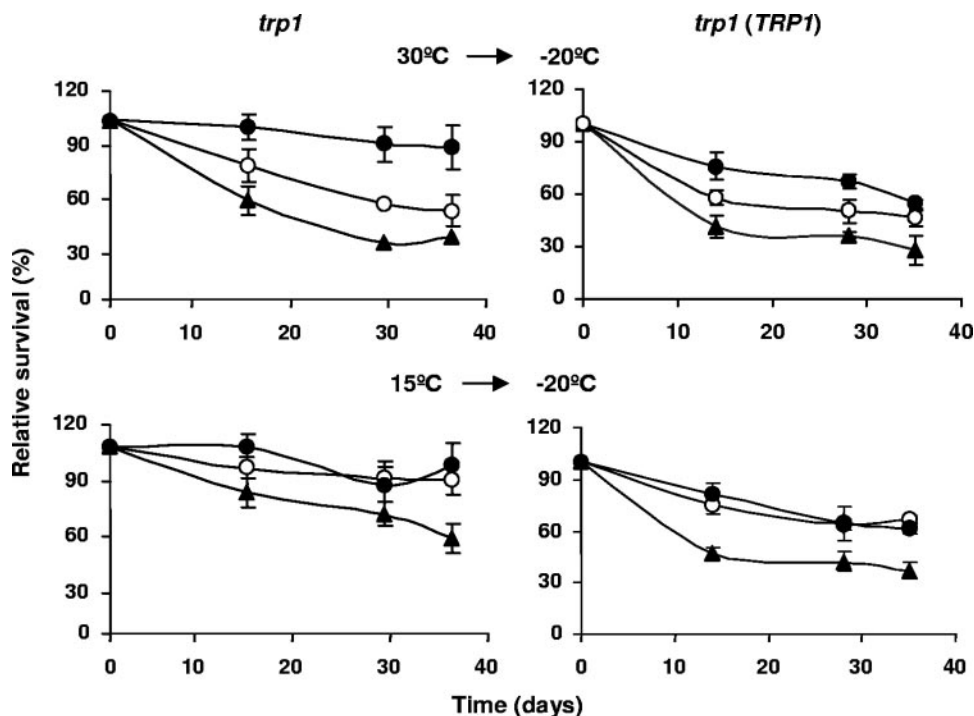


FIG. 2. Fluidization of yeast lipids enhances tolerance to freezing. Cell cultures of the *trp1* and *trp1 TRP1* *S. cerevisiae* strains, wild-type W303-1A (\blacktriangle) and transformants overexpressing *FAD2-1* (\circ) and *FAD2-3* (\bullet), were grown at 30°C (OD₆₀₀ of 0.4 to 0.6) and transferred directly to -20°C or preincubated at 15°C for 24 h, prior the shift to -20°C. After 14, 28, and 35 days, cell samples were thawed at 30°C for 30 min, diluted, and plated onto solid YPD, and the percentage of survival was determined. Values represent the means of at least three independent experiments. The error associated with the points was calculated by using the formula: $(1.96 \times SD)/\sqrt{n}$, where SD is the standard deviation and n is the number of measurements.

to that obtained by overexpression of other plant *FAD2* genes, which range from 10 to 50% (11, 13, 19, 25). More diunsaturated fatty acids were produced at 15°C than at 30°C, especially in *FAD2-1* transformants. In this respect, reports of the expression of *Arabidopsis FAD2* in yeast have yielded contradictory results, in which the amounts of 16:2 and 18:2 could increase at low temperatures (13) or remain constant (11). We found that the unsaturation index of lipids in both Trp⁺ and Trp⁻ W303FAD2-1 cells varied from 0.74 to 0.79 at 30°C to 0.94 to 0.97 at 15°C, a difference that has been attributed to the low thermal stability of the *FAD2-1* isoform (45). However, the overexpression of the sunflower *FAD2* genes did not increase the total unsaturated fatty acid content. This fact could be explained by possible feedback inhibition of Ole1p, since exogenous 18:2 in the culture medium could repress transcription of *OLE1* (10).

Increasing the unsaturation index of yeast lipids fluidized the yeast membrane and altered the stress response of yeast cells. The finding that biosynthesis of 16:2 $\Delta^{9,12}$ and 18:2 $\Delta^{9,12}$ fatty acids increased tolerance to salt stress and freezing was not completely unexpected. There are previous reports that suggest that membrane lipid composition is correlated with tolerance to different stresses, including heat shock (51), heavy metals (17), and exposure to the herbicide 2,4-dichlorophenoxyacetic acid (61). Survival following freezing/thawing might also depend on the physical properties of the membrane. Below 0°C, cells are injured by the formation of ice crystals, which results in macromolecule and membrane denaturation (33).

The growth of ice crystals during frozen storage could further degrade the plasma membrane (65). Thus, changing the fluidity of the lipid bilayer may help prevent or alleviate membrane damage due to freezing and contribute to cell survival.

The same protective mechanism may also operate in cells exposed to hyperosmolarity, since osmotic stress reduces cell membrane fluidity (27), which influences membrane permeabilization and cell death (41). We found that fluidization of the yeast membrane produced a moderate increase in Na⁺ tolerance but had no effects on resistance to pure osmotic stress. In *S. cerevisiae*, Na⁺ is extruded by both the P-type ATPase Ena1p (30) and the H⁺-antiporter Nha1p (21). In addition, Na⁺ compartmentation is mediated by vacuolar antiporters (48). All of these mechanisms of ion homeostasis depend on membrane proteins, whose activity might be affected by changes in membrane fluidity. Phospholipid composition of the membrane affects membrane-associated processes, such as plasma membrane ATPase activity (47), the higher proton motive force (34), and the transport of various amino acids (58).

Increased unsaturation of yeast lipids altered the growth profile of W303-1A (*trp1*) cells in response to ambient temperature. Unlike previous reports (40), dienoic fatty acid-enriched yeast cells grew slightly faster at 30°C than did wild-type cells. Similar results were observed at 37°C (data not shown). Their growth at low temperatures was also greatly reduced, but the cold sensitivity phenotype was alleviated by increasing tryptophan availability and completely overcome by tryptophan pro-

totrophy. No phenotypic differences were detected in Trp⁺ transformants grown at 30°C or 37°C (data not shown).

Tryptophan uptake has been termed the Achilles' heel of yeast physiology (2), since under a variety of stress conditions, it becomes a limiting factor for cell growth. The sensitivity of tryptophan permeases to changes in membrane fluidity may also determine the growth temperature profile of *S. cerevisiae* (1). Trp⁻ yeast cells that overproduce Tat2p, a high-affinity tryptophan transporter (46), grow better than the wild-type cells at 10 or 15°C, while their growth at 37°C is relatively reduced (1). Thus, Tat2p activity may be sensitive to the changes in fatty acid composition resulting from overexpression of sunflower *FAD2* desaturases.

Increased unsaturation of yeast lipids may also affect the protein sorting mediated by lipid rafts and the final destination of key membrane proteins. Association with lipid rafts, a sphingolipid- and sterol-rich membrane domain (50), plays an essential role in the correct localization of proteins such as Tat2p (59), Ole1p (56), or Pma1p (6, 7), the major plasma membrane H⁺-ATPase in *S. cerevisiae*. Mutations in *PMA1* result in cold sensitivity and Na⁺ resistance (22, 64), phenotypes shared by Trp⁻ *FAD2*-overexpressing cells. Thus, changes in the unsaturation index of lipids could affect the localization of key proteins and thereby cause pleiotropic phenotypes.

The data presented here provide direct evidence that overexpression of desaturases can be used to increase the tolerance of yeast cells to freezing. This trait is critical in determining an optimal leavening of lean and sweet frozen-dough products, and increasing the resistance of industrial yeasts to freezing is one of the most important biotechnological challenges in this field (42). Altering fatty acid composition and content by expressing heterologous desaturases could also be used to modify lipid microdomains and to study their function in cell signaling, polarity, and sorting. Thus, the results reported in this study have both basic and applied significance.

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