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Comparison of the metabolic response to over-production of p-coumaric acid in two yeast strains

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Transcriptome
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A B S T R A C T

The development of robust and efficient cell factories requires understanding of the metabolic changes triggered by the production of the targeted compound. Here we aimed to study how production of p-coumaric acid, a precursor of multiple secondary aromatic metabolites, influences the cellular metabolism of Saccharomyces cerevisiae. We evaluated the growth and p-coumaric acid production in batch and chemostat cultivations and analyzed the transcriptome and intracellular metabolome during steady state in low- and high-producers of p-coumaric acid in two strain backgrounds, S288c or CEN.PK.

We found that the same genetic modifications resulted in higher production of p-coumaric acid in the CEN.PK background than in the S288c background. Moreover, the CEN.PK strain was less affected by the genetic engineering as was evident from fewer changes in the transcription profile and intracellular metabolite concentrations. Surprisingly, for both strains we found the largest transcriptional changes in genes involved in transport of amino acids and sugars, which were downregulated. Additionally, in S288c amino acid and protein biosynthesis processes were also affected.

We systematically overexpressed or deleted genes with significant transcriptional changes in CEN.PK low and high-producing strains. The knockout of some of the downregulated transporters triggered a 20–50% improvement in the synthesis of p-CA in the CEN.PK high-producing strain. This study demonstrates the importance of transporters in the engineering of cell factories for production of small molecules.

1. Introduction

Plants produce a wide range of secondary metabolites as a protective mechanism to stresses caused by bacterial or viral infections, ultraviolet radiation, wounds, and other biotic and abiotic factors. Nearly 15% of these metabolites are phenolic compounds derived from the aromatic amino acids L-tyrosine, L-phenylalanine or L-tryptophan (Wink, 2010). Numerous aromatic secondary metabolites are available on the market as therapeutic agents, dyes, fragrances, and flavors. The majority of these compounds are currently synthesized chemically or isolated from plants (Bourgaud et al., 2001), however recently there have been significant advances in engineering industrial microbes, e.g., Escherichia coli and S. cerevisiae, for production of aromatic secondary metabolites by fermentation. A few biotech-derived aromatics are already on the market, such as phenylalanine, resveratrol, vanillin, steviol glucoside, and others. Additionally, many aromatic metabolites have been produced in microbial cell factories at proof-of-concept levels, but the strains, fermentation and downstream processes need further development before the production becomes economically feasible. These compounds include naringenin, genistein, kaempferol, fisetin, melatonin, and many others (Koopman et al., 2012; Trantas et al., 2009; Santos et al., 2011; Leonard et al., 2009; Stahlhut et al., 2015; Krivoruchko and Nielsen, 2015; Li et al., 2015; Germann et al., 2016).

An important step towards improved microbial cell factories is a better understanding of how the engineered cells respond to production of target compounds (Nielsen and Keasling, 2016). For this purpose, omic-level characterization of the strains is useful since the organism can be studied at different levels and the information can be assessed in...
2.1. Plasmids and strains

E. coli DH5α was used for cloning procedures. The fragments used for overexpression of genes were amplified by PCR using primers and templates as described in the Tables S1 and S2. The fragments were amplified from the genomic DNA of S. cerevisiae CEN.PK102-3B (MATa ura3-52 his3Δ1 leu2-3/112 MAL2-8c SUC2) and E. coli NST 74. The gene encoding tyrosine ammonia-lyase from Flavobacterium johnsoniae (FJTAL) was as described in (Jendresen et al., 2015). The amplified gene-encoding fragments were cloned together with strong constitutive promoters into EasyClone integrative plasmids by USER cloning (Jensen et al., 2014; Jessop-Fabre et al., 2016). The clones were tested for correct insertion of gene/promoter fragments by colony PCR using the primers summarized in the Table S1 and the resulting plasmids were verified by sequencing. The list of the constructed vectors can be found in Table 1.

S. cerevisiae CEN.PK113-7D was obtained from Peter Köll (Johann Wolfgang Goethe-University Frankfurt, Germany). The strain BY4741, a derivative of strain S288c, was obtained from EUROSCARF. Transformation of yeast cells was performed using the lithium acetate method (Gietz et al., 2002). The strains were selected on synthetic drop-out medium (Sigma-Aldrich) and the genetic modifications were confirmed by colony PCR. The yeast strains used in this study are listed in Table 2 and Table S3.

2.2. Media and cultivations.

We prepared a mineral medium for the batch fermentation according to Verduyn et al. (1992). Glucose concentration in batch medium was 40 g L⁻¹. The feed medium for chemostats was prepared in the same way, but the amount of glucose was reduced to 10 g L⁻¹ and the medium was supplemented with 0.2 ml L⁻¹ of 2 M KOH and one drop of antifoam 204 (Sigma-A 8311) per 20 L of medium. The pre-culture was done by inoculating a yeast colony into 50 ml of mineral medium in a 250-ml baffled shake flask and incubating the culture with shaking at 200 rpm at 30 °C for around 12 h. Before the pre-culture reached OD₆₀₀ of ca. 2, it was used to inoculate a bioreactor to a starting optical density of 0.05.

The fermentations were performed in DasGip 1-L stirrer-pro vessels (Eppendorf, Jülich, Germany), using the working volume of 500 ml. The temperature was 30 °C, agitation was at 600 rpm and aeration at 1vvm. pH was monitored with a pH sensor (Mettler Toledo, Switzerland) and pH was maintained at 5.0 ± 0.05 by automatic addition of 2 M KOH. Dissolved oxygen was above 30% throughout the fermentation as measured by the polarographic oxygen sensor (Mettler Toledo, Greifensee, Switzerland). The completion of the batch phase was determined by monitoring CO₂ in the exhaust gas, when the second CO₂ peak, corresponding to ethanol consumption phase, declined. We then initiated constant feed to obtain glucose-limited steady-state with dilution rate of 0.100 ± 0.005 h⁻¹. The volume was kept constant using an overflow pump. The samples for transcriptome and metabolome analysis were taken after 4 residence times of steady-state growth. Four technical replicates were taken from each reactor for transcriptome and metabolome analyses. Each strain was fermented twice to obtain 2 biological replicates.

2.3. Analytical methods

For analysis of extracellular metabolites and the biomass, we withdrew ca. 3 ml samples from the reactor. 1 ml of the sample was centrifuged at 11,000 g for 5 min and stored at −20 °C until HPLC analysis for glucose and organic acids. For p-CA analysis in the optimized strains (ST4288 and ST4353) we mixed 1 vol of sample with 9 volumes of 50% ethanol, whereas for the non-optimized strains (ST4408 and ST4397) we mixed 1 vol of sample with 1 vol of 50% ethanol. This was done to dissolve the p-CA that may have precipitated from the broth due to poor solubility in water. These samples were also centrifuged at 11,000 × g for 5 min and stored at −20 °C until further analysis.

The analysis of glucose, glyceral, ethanol, and organic acids was performed on Dionex Ultimate 3000 high-performance liquid chromatography (HPLC) system (Dionex Softron GmbH, Germany), with an Aminex HPX-87H column (Bio-Rad) at 65 °C, using 5 mM H₂SO₄ as the mobile phase with a flow rate of 0.6 ml/min.

Quantification of p-CA was performed as described in Rodriguez et al. (2015) using a HPLC (Thermo Fisher Scientific), with a Discovery HS F5 150 mm × 2.1 mm column (particle size 3 µm). The samples were analyzed using a gradient method with two solvents: (A) 10 mM ammonium formate pH 3.0 and (B) acetonitrile at 1.5 ml min⁻¹. The p-CA was detected by absorbance at 277 nm and the retention time was 4.7 min. The area under the curve was integrated with Chromleon software 7. The quantification of p-CA was performed based on 5 points calibration curve in the range of 0.1–1 mM. For the dry cell weight measurement 5 ml of culture broth was filtered through a 0.45 µm filter membrane, after that the membrane was dried at 95 °C for 24 h and cooled down in a desiccator. The dry cell weight was calculated by measuring the weight increment of the dried filter.

2.4. Transcriptome analysis

Samples for RNA extraction were taken after four retention times of...
steady-state fermentation by rapidly withdrawing 5 ml of culture and injecting it into a 50 ml falcon tube with ca. 30 ml of crushed ice, the samples were immediately centrifuged at 4000 rpm for 5 min at −20 °C. The supernatant was discarded, the pellet was frozen in liquid nitrogen and stored at −80 °C until further analysis. The RNA extraction was performed using the RNasy Mini Kit (QIAGEN). The DNA was removed from the sample using Turbo DNA-free Kit (Ambion). The purified RNA samples were analyzed with a 2100 Bioanalyzer (Agilent Technologies, Inc., Santa Clara, CA) and stored at −80 °C until further analysis.

The sequencings libraries were prepared in four replicates using a TruSeq® Stranded mRNA sample preparation kit LT (Illumina Inc.). The final concentration of each cDNA library was measured by Qubit® 2.0 Fluorimeter and Qubit dsDNA Broad Range assay (Life Technologies). Average dsDNA library size was determined by using the Agilent DNA Fluorimeter and Qubit dsDNA Broad Range assay (Life Technologies). The sequencing libraries were prepared in four replicates using a NextSeq 500/550 Mid Output v2 Reagent kit (150 cycles, Illumina Inc.). Libraries were normalized and pooled in 10 mM Tris-Cl, pH 8.0, plus 1% BSA. The library pool was loaded into the flow cell provided in the NextSeq. 500/550 Mid Output v2 Reagent kit (150 cycles, Illumina Inc.). Libraries were sequenced on the NextSeq (Illumina Inc.) platform with a paired end protocol and read lengths of 75 nt. RNA-seq data have been deposited in the ArrayExpress database at EMBL-EBI (www.ebi.ac.uk/arrayexpress) under accession number E-MTAB-6208.

2.5. Metabolomics analysis

Sampling, quenching and washing of the intracellular metabolites was performed as described by Canelas et al. (2009). The analysis of amino acids and other organic acids was performed according to Khoomrung et al. (2015). The analysis of the derivatized metabolites was performed using a Focus GC ISQ LIT single quadrupole GC-MS (Thermo Fisher Scientific, USA). The column was a Zebron ZB-1701 GC column (30 m 0.25 mm I.D., 0.25-mm film thickness, Phenomenex, Macclesfield, UK). The metabolites were identified by comparing their retention times and mass spectrum profiles with the authentic standards or the mass spectra from the National Institute of Standards and Technology (NIST), USA library. The data was processed using the Quan browser function in the Xcalibur software version 2.2 (Thermo Fisher Scientific).

2.6. Data analysis

The alignment of sequencing reads to the reference genome was performed using TopHat, the assembly and quantification of the expression levels was developed with Cufflinks and a preliminary analysis of the data was performed with CummeRbund, the methods were used as described by Trapnell et al. (2012). Paired comparisons were performed between optimized and non-optimized strains on each background: the strain ST4288 was compared with the strain ST4408 and the strain ST4397 was compared with the strain ST4353.

The gene set analysis was performed using the R package Piano (Väremo et al., 2013), a platform for integrative analysis of omics data. The p-values and the fold changes were used as input data and two types of analysis were performed with this program: first a gene-set analysis with the reporter algorithm for gene ontology (GO) and second a gene set analysis using the reporter metabolites. The genome-metabolite network was obtained from the S. cerevisiae metabolic model iTO977 (Osterlund et al., 2013). The gene sets and reporter metabolites with a distinct directional p-value < 0.05 were chosen for the analysis.

The network topology analysis was performed using Kiwi a tool for visualization and interpretation of gene sets analysis (Väremo et al., 2014). This tool allows integrating the results of the gene set analysis with a gene set interaction network. The input for this analysis was a gene set interaction network obtained from the S. cerevisiae metabolic model iTO977 and the results from the gene set analysis using reporter metabolites.

For the metabolomics data, we did a PCA analysis in MATLAB to identify the differences between the four strains object of this research and to establish the differences between the engineered and non-engineered strain we did volcano plots based on the results of a t-test comparison between optimized and non-optimized strains on each background.

Table 1

<table>
<thead>
<tr>
<th>Plasmids used in this study.</th>
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<table>
<thead>
<tr>
<th>Name</th>
<th>Parent plasmid</th>
<th>Properties</th>
<th>Reference</th>
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<tbody>
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<td>pCB257</td>
<td>– X-3, lopP, KLEU2</td>
<td></td>
<td>Jensen et al. (2014)</td>
</tr>
<tr>
<td>pCB258</td>
<td>– X-3, lopP, SphIS</td>
<td></td>
<td>Jensen et al. (2014)</td>
</tr>
<tr>
<td>pCB390</td>
<td>– X-3, lopP, KREU3</td>
<td></td>
<td>Jensen et al. (2014)</td>
</tr>
<tr>
<td>pCB8326</td>
<td>pCB258</td>
<td></td>
<td>Rodriguez et al. (2015)</td>
</tr>
<tr>
<td>pCB303523</td>
<td>pCB390</td>
<td></td>
<td>This study</td>
</tr>
<tr>
<td>pCB303524</td>
<td>pCB390</td>
<td></td>
<td>This study</td>
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</table>

Table 2

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<td>ST4360</td>
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<td>ST4361</td>
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<td>ST4195</td>
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<td>ST4085</td>
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<td>ST4088</td>
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<tr>
<td>ST4089</td>
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</table>

*Table 2* Strains used in this study.

The strains to these changes, we constructed two strains in each of the genetic backgrounds (CEN.PK and S288c). The resulting high-producing CEN.PK strain did not have any gene regulations in gene sets related to the synthesis of amino acids and transport functions and iron metabolism, which was observed for both strain backgrounds. Additionally, S288c strain had remarkable down-regulations in gene sets related to the synthesis of amino acids and proteins.

### 3. Results

#### 3.1. Physiological characterization of low and high producers of p-coumaric acid

To understand the fundamental metabolic changes triggered by the overproduction of p-CA, and the response of different background strains to these changes, we constructed two strains in each of the genetic backgrounds (CEN.PK and S288c). The “low-producers” were generated by overexpressing tyrosine ammonia lyase from Flavobacterium johnsonae under control of the P<sub>TEF1</sub> promoter. The “high-producers” were created by additional overexpression of aroL under control of the P<sub>CEN.PK</sub> promoter, ARO7<sup>ΔAHO1416</sup> and ARO4<sup>ΔARS2111</sup> from S. cerevisiae under control of the promoters P<sub>TEF1</sub> and P<sub>PGK1</sub> respectively and deletion of ARO10 and PDC5. The resulting 4 strains were analyzed in batch and glucose-limited chemostat cultivations.

The concentrations of p-CA in batch and continuous cultivations were higher in the CEN.PK strains in comparison to the S288c strains with the same genetic modifications (Table 3). The glycerol yield was higher in the S288c strains in comparison to the CEN.PK strains. In batch fermentations, the optimized strains had lower biomass yield and higher acetate accumulation than the non-optimized ones.

#### 3.2. Transcriptional response of the strains to the synthesis of p-coumaric acid

For analysis of the differential gene expression, we did pairwise comparisons between the optimized and non-optimized strains for p-CA production: CEN.PK strains (ST4288 and ST4408) and the S288c strains (ST4353 and ST4397).

Significantly up and down-regulated gene sets were identified through a gene set analysis using GO terms (p adjusted value < 0.05). The engineered high-producing CEN.PK strain did not have any gene sets that were significantly upregulated in comparison to the low-producing CEN.PK strain. For S288c strain, however, gene sets related to DNA helicase activity, telomerase maintenance and ribonuclease activity were upregulated (Fig. 1). Among the down-regulated gene sets were transport functions and iron metabolism, which was observed for both strain backgrounds. Additionally, S288c strain had remarkable down-regulations in gene sets related to the synthesis of amino acids and proteins.

To elucidate the biological connections between the gene sets, we did a network analysis of the gene sets using metabolite reporters (Patil and Nielsen, 2005; Väremo et al., 2013), and used the network visualization tool Kiwi for visualizing the results (Väremo et al., 2014). The network analysis allows integrating the information from the gene set analysis with metabolite interactions from a genome-scale metabolic model of yeast provided via the PIANO toolbox (Väremo et al., 2013).

For the CEN.PK strain we observed significant downregulation of genes correlated to eight amino acids, proton H(+) and galactose. All the amino acids mapped in the network have in common upregulations in AGP1 and GAP1 together with downregulations in BAP3 and BAP2 and TAT1, all of them are involved in the transport of amino acids (Fig. 2A, Fig. S1).

One of the metabolites correlated to downregulated genes is L-tyrosine, the precursor of p-CA, the network analysis shows that besides correlation to downregulation of transporters, this metabolite is related to a strong upregulation in the aromatic aminotransferase II ARO9 involved in the conversion of p-hydroxyphenylpyruvate into L-tyrosine, i.e. the first step of tyrosine catabolism. Finally, proton H(+) is mainly correlated to downregulations in genes involved in transport functions (BAP2, TAT1, ALP1, TOPO1, BiOS, VHT1) and α-galactose is mainly correlated to downregulation of hexose transport (HXT10, HXT14).

The strain S288c had downregulated genes correlated to 5 amino acids (L-methionine, L-tyrosine, L-tryptophan, L-glutamate and L-orotic acid), three sugars (α-fructose, alpha-D-glucose and alpha-D-mannose), acetaldehyde and 2-oxoglutarate (Fig. 2B, Fig. S2).

The amino acids reported in the network analysis had in common the downregulation of BAP2, TAT1 and the upregulation of AGP1. These genes are correlated to amino acid transmembrane transporter activity. We found two aromatic amino acids in the network: L-tyrosine and L-tryptophan, they share downregulations in genes related to amino acids transport (BAP2 and TAT1), and they differ in the upregulations when L-tyrosine has a strong upregulation in ARO9 and ALD3. L-tryptophan has a strong upregulation in MSY1 (Fig. 2B, Fig. S2).

Finally, the metabolites 2-oxoglutarate, L-glutamate and L-ornithine are correlated to downregulated genes involved in the synthesis and transport of amino acids. L-glutamate has a central role in the metabolic network and it is correlated to downregulation of ASN1, ADE4, CAR2 and TRP2, genes involved in the synthesis of amino acids. The three sugars reported in the network are correlated to downregulations in genes involved in the transport of sugars (HXT2 and HXT16).

### Table 3

<table>
<thead>
<tr>
<th>Background strain</th>
<th>CEN.PK</th>
<th>S288c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized for p-CA production</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Batch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum specific growth rate $\mu_{\text{max}}$ (h&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.334 ± 0.006</td>
<td>0.294 ± 0.006</td>
</tr>
<tr>
<td>Final titer of p-CA (g L&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.202 ± 0.005</td>
<td>2.405 ± 0.054</td>
</tr>
<tr>
<td>Biomass yield on glucose (g g&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.477 ± 0.044</td>
<td>0.268 ± 0.093</td>
</tr>
<tr>
<td>p-CA yield on glucose (g g&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.001 ± 0.000</td>
<td>0.013 ± 0.000</td>
</tr>
<tr>
<td>Glycerol yield on glucose (g g&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.019 ± 0.001</td>
<td>0.018 ± 0.002</td>
</tr>
<tr>
<td>Acetate yield on glucose (g g&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.010 ± 0.003</td>
<td>0.014 ± 0.002</td>
</tr>
<tr>
<td>Ethanol yield on glucose (g g&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.309 ± 0.001</td>
<td>0.293 ± 0.004</td>
</tr>
<tr>
<td>Final biomass dry weight (g DCW L&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>13.198 ± 0.279</td>
<td>12.566 ± 0.056</td>
</tr>
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</table>

**Chemostat (steady-state data)**

| Titer of p-CA (g L<sup>-1</sup>) | 0.117 ± 0.000 | 0.507 ± 0.013 | 0.081 ± 0.005 | 0.410 ± 0.024 |
| Biomass dry weight (g DCW L<sup>-1</sup>) | 4.647 ± 0.156 | 4.670 ± 0.181 | 4.625 ± 0.165 | 4.620 ± 0.094 |
| Glucose (g L<sup>-1</sup>) | ND | ND | ND | ND |
| Glycerol (g L<sup>-1</sup>) | ND | 0.021 ± 0.004 | ND | 0.013 ± 0.001 |
| Acetate (g L<sup>-1</sup>) | ND | ND | ND | ND |
| Ethanol (g L<sup>-1</sup>) | ND | ND | ND | ND |

ND – not detected.
3.3. Changes of intracellular metabolome in response to the synthesis of p-coumaric acid

To identify the differences in the metabolome caused by overproduction of p-CA and by different genetic backgrounds, we did a PCA analysis. The first component of the PCA accounted for 82% of the variability and showed significant differences between the background strains CEN.PK and S288c, the metabolites with higher contributions to this component are phosphoric acid, disilaheptane, L-ornithine, glutamic acid, lysine and citrate, all of them related to higher concentration of the metabolites in the CEN.PK background whereas the strain S288c is related to higher values of cis-9-hexadecanoic acid (Fig. 3).

The second component explains 8% of the variability and establishes the differences between optimized and non-optimized strains for the two backgrounds tested, the metabolites with higher contributions to this component are glutamine and L-tyrosine with higher concentrations for the engineered strains whereas the non-optimized strains are related to higher concentrations of malic acid.

A t-test was performed comparing the non-optimized and optimized strain of each background, aiming to identify which metabolites has significant differences when the cells are producing p-CA. The significant differences for both of the background strains tested are mainly related to the low concentration of metabolites in the optimized strains. For the CEN.PK strains, we found significant differences in four metabolites: two amino acids (L-valine and L-threonine), malic and citric acid.

Fig. 1. Gene sets with significant differences in the optimized strains for p-CA production in comparison to the non-optimized strains.

Fig. 2. Network topology analysis identified metabolites with significant differences in the optimized strains in comparison to the non-optimized strains. The nodes are resized according to the gene-set significance, the colors reflect the direction of change of the gene-set, the edges between two metabolites symbolized how close they are in the metabolite-metabolite network and the thickest edges link the metabolites that are in close proximity to each other.

A. comparison between CEN.PK strains; B. Comparison between S288c strains.

Fig. 3. Score and loading plot from the principal component analysis based on the metabolome data of optimized and non-optimized strains in the S. cerevisiae backgrounds CEN.PK and S288c.
acid. For the S288c strain, we found significant differences in 5 amino acids, phosphoric acid, malic acid, citric acid, and cis-9-hexadecanoic acid (Fig. 4). There is bigger variation between the low and high-producing S288c strains than CEN.PK strains.

3.4. Engineering of highly upregulated or downregulated genes

As the next step, we wanted to investigate how p-coumaric acid production could be influenced by targeted deletion or upregulation of the genes that showed significant changes in the transcriptome analysis. We chose 24 genes that were significantly upregulated or downregulated. We carried out single knock-outs or overexpressions of these genes in strains ST4964 and ST4965, which were generated from correspondingly strains ST4288 and ST4408 by additional expression of a cas9 gene to enable simplified genome editing (Stovicek et al., 2015). Knock-outs of 9 genes could not be obtained. It may either be due to inefficient guiding gRNA or due to conditional lethality of these genes. The overexpression was realized by inserting an extra copy of the gene under control of a strong constitutive promoter TEF1. All the resulting strains were cultivated in feed-in-time medium and the optical densities and titer of p-coumaric acid were measured. None of the overexpressions resulted in significant change in the p-CA titer in either a low-producing nor high-producing strains (Fig. S3). The deletions did not influence p-CA titer in the low-producing strains, however, we observed improvement of p-CA production for seven gene deletions in the high-producer strain ST4964 background (Fig. S4, Table 4). All the seven deletion targets that triggered higher amounts of p-CA were involved in the transport of amino acids, polyamines, and sugar.

The highest improvement in p-CA synthesis was obtained by deleting TAT1, encoding a tyrosine and tryptophan amino acid transporter. The knockout of this gene triggered a 50% increase of p-CA titer. Strains with knockouts of polyamine transporter TPO1 and arginine transporter ALP1 resulted in 40–45% higher titer. Finally, deletion of amino acids transporters (BAP2, AGP3), acetate transporter ADY2 and galactose transporter GAL2 gave 20–30% improvement (Table 4, Figs. S4 and S5).

4. Discussion

In our study, engineered high-producer strain with CEN.PK background gave 20–25% higher p-CA titers in batch and continuous cultivations in comparison with S288c strain engineered identically. Moreover, the CEN.PK-producer had a higher maximum specific growth rate $\mu_{\text{max}}$ than S288c-producer. Transciptome analysis showed that the CEN.PK strain was less affected by engineering towards higher p-CA production than the S288c strain, as the number of significantly up-/down-regulated genes was correspondingly 652 and 1927 amongst others, strain S288c had downregulations in gene sets involved in amino acid and protein biosynthesis. This suggests that CEN.PK may be a better platform strain for production of aromatic compounds than the S288c strain.

The transcriptome analysis also revealed downregulations in transport functions in the engineered strains of both backgrounds, which could be a response to the stress triggered by production of p-CA. Previous studies on plasma membrane integrity and ethanol stress in S. cerevisiae have reported that yeast cells react to chemical stress by downregulating the transport of some metabolites and by decreasing gene expression in energy-demanding processes (Stanley et al., 2010, Madeira et al., 2010; Leao and van Uden, 1984).

For the engineered S288c strain, metabolomics analysis revealed lower concentrations of phosphoric acid, L-ornithine and glutamic acid, which correlates with downregulation of the gene sets involved in the synthesis of proteins and amino acids. Interestingly previous research on S. cerevisiae stress responses to oxidative stress had shown diminution in the synthesis of proteins as a prevention mechanism under potentially error-prone conditions (Shenton and Grant, 2003a).

We observed higher accumulation of glycerol by the engineered strains than in non-optimized strains. Synthesis of glycerol is known as an important factor in the control of osmoregulation and of redox balance (Hohmann et al., 2007; Muzzey et al., 2009). Another interesting metabolite is cis-9-hexadecanoic acid; this metabolite had higher concentrations in the S288c strain in comparison to CEN.PK strain; we propose that the stress originating from the production of p-CA may trigger the synthesis of this fatty acid in the S288c strains. It had been previously reported that genetically engineered strains with a higher concentration of cis-9-hexadecanoic acid were more tolerant to temperature and oxidative stress (Steele et al., 1994; Jameson, 1998).

Overexpression or knock-outs of genes with changed transcriptional profile did not affect p-CA production in low-producing strain background (ST4965). Most likely, in this strain the flux is primarily limited by the biosynthesis of tyrosine precursor and hence modulating the expression of primarily transport and stress-related genes could not influence the production significantly. The situation was different for the high-producing strain background (ST4964), where knock-outs of seven transport-related genes improved p-CA titer by 20–50%.

Particularly, the deletion of the tyrosine and tryptophan transporter TAT1 resulted in 50% improvement of p-CA titer. Possibly, the deletion of TAT1 resulted in reduction of the leakage of tyrosine from the cells.

Table 4

<table>
<thead>
<tr>
<th>Strain</th>
<th>Name</th>
<th>Name description</th>
<th>% improvement of p-CA titer</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST5935</td>
<td>TAT1</td>
<td>Tyrosine and tryptophan amino acid transporter</td>
<td>48 ± 21</td>
</tr>
<tr>
<td>ST5937</td>
<td>TPO1</td>
<td>Transporter of polyamines</td>
<td>45 ± 13</td>
</tr>
<tr>
<td>ST5938</td>
<td>ALP1</td>
<td>Arginine transporter</td>
<td>39 ± 11</td>
</tr>
<tr>
<td>ST5939</td>
<td>AGP3</td>
<td>High-affinity glutamine permease</td>
<td>27 ± 29</td>
</tr>
<tr>
<td>ST5940</td>
<td>ADY2</td>
<td>Acetate transporter</td>
<td>26 ± 16</td>
</tr>
<tr>
<td>ST5942</td>
<td>GAL2</td>
<td>Galactose permease</td>
<td>23 ± 10</td>
</tr>
<tr>
<td>ST5949</td>
<td>BAP2</td>
<td>Branched-chain amino acid permease</td>
<td>22 ± 25</td>
</tr>
</tbody>
</table>
hence more could serve as substrate for p-CA production. Interestingly, overexpression of the same genetic targets did not lead to any significant changes in p-CA titer. The number of transporter proteins per cell is one-two orders of magnitude lower than the cytosolic proteins and overexpression of a transporter gene may not result in a significant increase of transporter protein content simply due to the membrane crowding.

Our study highlights the importance of transporters when engineering cell factories for production of small molecules. Future studies are warranted on identifying the transporters responsible for the efflux of p-CA and intermediates and on using this knowledge for further strain improvement.

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Declaration of interest

The authors declare no competing interests.

Contributions

AR, IB and JN conceived and designed the study and analyzed the results. AR,YC and SK did the experimental work. AR, YC, EO and SK processed and analyzed the data. AR and IB drafted the manuscript and all authors read, edited and approved the final manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ymben.2017.10.013.

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