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RapidRIP quantifies the intracellular metabolome of 7 industrial strains of E. coli

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ABSTRACT

Fast metabolite quantification methods are required for high throughput screening of microbial strains obtained by combinatorial or evolutionary engineering approaches. In this study, a rapid RIP-LC-MS/MS (RapidRIP) method for high-throughput quantitative metabolomics was developed and validated that was capable of quantifying 102 metabolites from central, amino acid, energy, nucleotide, and cofactor metabolism in less than 5 minutes. The method was shown to have comparable sensitivity and resolving capability as compared to a full length RIP-LC-MS/MS method (FullRIP). The RapidRIP method was used to quantify the metabolome of seven industrial strains of E. coli revealing significant differences in glycolytic, pentose phosphate, TCA cycle, amino acid, and energy and cofactor metabolites were found. These differences translated to statistically and biologically significant differences in thermodynamics of biochemical reactions between strains that could have implications when choosing a host for bioprocessing.

1. Introduction

Traditional high-throughput screening approaches in metabolic engineering have primarily relied upon basic physiology markers of strain performance. Physiological markers often include basic input/output parameters such as growth rate, substrate uptake rate, product excretion rate, yield, and productivity. While useful, these markers give little information on the underlying strain physiology. Omics data types (e.g., transcriptomics, metabolomics, fluxomics, etc.) could potentially provide a richer and deeper understanding of strain performance, which would allow more informed engineering decisions (McCloskey et al., 2013). However, -omics data types are often not utilized in routine screening of new production strain candidates because of high costs and low throughput (Hansen et al., 2017). Of the various -omics data types available, metabolomics provides the greatest potential to gain rich and deep insight on strain physiology at a lower cost and with faster scan rates, the potential to reduce method run-times to less than 5 min with minimal compromise to chromatographic resolution or quality of acquired peaks is now possible (Guder et al., 2017). However, current fast separation methods often compromise on the ability to resolve important biological isomers (e.g., glucose 6 phosphate and glucose 1 phosphate). In addition, fast separation methods often compromise on the separation of structurally similar compounds with interfering signals (e.g., AMP, ADP, and ATP) that may compromise accurate quantitation. The ability to separate these species is critical for quantitative modeling of biological systems (Almqquist et al., 2014; Henry et al., 2006; Jamshidi and Palsson, 2008; Miskovic et al., 2017; Saa and Nielsen, 2016). An ultra high-throughput metabolomics method less than 5 min that is able to resolve of biologically important isomers and provide complete separation of structural similar compounds with interfering transitions has yet to be demonstrated.

Escherichia coli are often used as a model prokaryote for genomic and physiological studies (Archer et al., 2011; Arifin et al., 2014; Ishii et al., 2007; Vijayendran et al., 2007; Yoon et al., 2012), and as host strains for industrial bioprocesses (Chae et al., 2017; S. Y. Choi et al.,...
2016; S. Choi et al., 2016; Park et al., 2011, 2007; Yim et al., 2011) owing to the rich toolset available for gene and expression modification (Dansken and Wanner, 2000; Jiang et al., 2015; Ronda et al., 2016; Wang et al., 2009) as well as accumulated historical knowledge base of biochemical understanding (Gue et al., 2013; Kanesha et al., 2017; Kesler et al., 2013; Monk et al., 2017). Seven commonly used strains in biotechnology applications include K-12 MG1655, K-12 W3110, K-12 DH5α, BL21, C, Crooks, and W. It has been shown that particular strains are better suited for different applications (Monk et al., 2016). For example, DH5α is often preferred in cloning applications (Song et al., 2015; Taylor et al., 1993), while BL21 is often preferred for expression of recombinant proteins (Marisch et al., 2013a; Robichon et al., 2011). It has also been shown that choice of host strain for production of a given compound can significantly impact production titers (Na et al., 2013). Various comparisons between the seven industrial strains of E. coli under bioprocess conditions or as host strains for a particular metabolic engineering endeavor have been described (Chae et al., 2010; Fathi-Roudsari et al., 2016; Marisch et al., 2013a, 2013b; Monk et al., 2016). However, a comprehensive comparison of the metabolomes between the strains does not yet exist. An understanding of the starting metabolite levels of the strains would give researchers a key piece of information when deciding which E. coli strains to use as a host in their particular bioprocess.

In this study, a rapid reverse phase ion-pairing liquid chromatography triple quadrupole mass spectrometry (RapidRIP) for the rapid quantification of the intracellular metabolome for routine screening applications was developed and validated. It was shown that the method was capable of quantifying 102 metabolites in less than 5 min with comparable resolution, sensitivity, and reproducibility to a 33 min RIF-MS/MS (FullRIP) method. The RapidRIP method was used to quantify the metabolome of seven industrial strains of E. coli. Significant differences in glycolytic, pentose phosphate, TCA cycle, amino acid, and energy and cofactor metabolites were found. These differences translated to strain-specific differences in reaction thermodynamics.

2. Material and methods

2.1. Biological material and growth conditions

Escherichia coli strains E. coli C (DSMZ 4860), E. coli Crooks (DSMZ 1576), E. coli DH5α (DSMZ 6897) E. coli W (DSMZ 1116), E. coli W3110 (DSMZ 5911) were obtained from DSMZ-Germany Collection of Microorganisms and Cell Cultures; E. coli BL21 (DE3) was purchased as competent cells from Agilent (Agilent Technologies), E. coli K-12 MG1655 (ATCC 700926). All cultures were grown in 25 mL of unlabeled or labeled glucose M9 minimal media (Sambrook and Russell, 2001) with trace elements (Fong et al., 2005) and sampled from a heat block in 50 mL autoclaved tubes that were maintained at 37 °C and aerated using magnetics.

Growth and sampling procedures for Pseudomonas, Mouse, and CHO are described in the Supplemental methods.

2.2. Materials and reagents

Uniformly labeled 13C glucose was purchased from Cambridge Isotope Laboratories, Inc. (Tewksbury, MA). Unlabeled glucose and other media components were purchased from Sigma-Aldrich (St. Louis, MO). LC-MS reagents were purchased from Honeywell Burdick & Jackson® (Muskegon, MI), Fisher Scientific (Pittsburgh, PA) and Sigma-Aldrich (St. Louis, MO).

2.3. LC-MS/MS instrumentation and data processing

Metabolites were acquired and quantified on an AB SCIEX Qtrap® 5500 mass spectrometer (AB SCIEX, Framingham, MA) using a ACQUITY UPLC HSS T3 Column (100 Å, 1.8 µm, 2.1 mm X 30 mm) and processed using MultiQuant® 3.0.1 as described previously (McCloskey et al., 2015). The acquisition method used for all transitions is given in Table S10.

2.4. Metabolomics

Internal standards were generated as described previously (McCloskey et al., 2014a, 2014b). All samples and calibrators were spiked with the same amount of internal standard taken from the same batch of internal standards. Calibration curves were run before and after all biological and analytical replicates. The consistency of quantification between calibration curves was checked by running a Quality Control sample that was composed of all biological replicates twice a day. Solvent blanks were injected every ninth sample to check for carryover. System suitability tests were injected daily to check instrument performance.

Metabolomics samples were acquired from triplicate cultures (1 mL of cell broth at an OD600 ~ 1.0) using a previously described method (Douglas McCloskey et al., 2014a, 2014b). A pooled sample of the filtered medium that was re-sampled using the FSF filtration technique and processed in the same way as the biological triplicates was used as an analytical blank. Extracts obtained from triplicate cultures and re-filtered medium were analyzed in duplicate. The intracellular values reported, unless otherwise noted, are derived from the average of the biological triplicates (n = 6). Metabolites in the pooled filtered medium with a concentration greater than 80% of that found in the triplicate samples were not analyzed due to high background interference. In addition, metabolites that were found to have a quantifiable variability (RSD > = 50%) in the Quality Control samples or any individual components with an RSD > = 80 were not used for analysis.

Missing values were imputed using a bootstrapping approach as coded in the R package Amelia II (Honaker et al., 2011) (version 1.7.4, 1000 imputations). Remaining missing values were approximated as ½ the lower limit of quantification for the metabolite normalized to the biomass of the sample. Prior to statistical analyses, metabolite concentration data were log transformed to generate an approximately normal distribution using the R package LMGene (Rocke et al., n.d.) (version 3.3, “mult” = “TRUE”, “lowessnorm” = “FALSE”). A Bonferroni-adjusted p-value cutoff of 0.01 as calculated from a Student’s t-test was used to determine significance between metabolite concentration levels. The glog-normalized values were used for downstream statistical analyses.

2.5. Thermodynamics

In vivo free energy change of reaction were calculated as described previously (McCloskey et al., 2014a, 2014b) using a recent genome-scale reconstruction of E. coli (Orth et al., 2011). In short, free energy of formation values taken from the eQuilibrator data base (Flamholz et al., 2012) were adjusted to physiologically estimated values for the cytosolic, periplasmic, and extracellular space for temperature (37 °C), pH (7.5, 7.0, and 7.0, respectively), and ionic strength (0.2 M). The 95% confidence intervals of the metabolomics concentrations were used to calculate the 95% confidence intervals of the free energies of reaction. Free energy changes of reaction with non-overlapping confidence intervals between the strains were defined as statistically significant. Free energy changes of reaction with confidence intervals with different signs between the strains were defined as biologically significant. Free energy changes of reaction were only compared for those reactions with sufficient measured metabolomics and compound free energy of formation data coverage (50% and 99% of all reactants and products, respectively). Concentration values for phosphate, water, hydrogen, oxygen, and carbon dioxide were estimated as 1e-3, 55.0, 0.034e-3, 0.055e-3, and 1.4e-3M, respectively. Concentration confidence intervals for missing metabolites were estimated as 1.58e-3M and 1.58e-6M. Free energy of formation confidence intervals not measured were estimated as biologically significant.
estimated using the group contribution method (Flamholz et al., 2012).

Thermodynamic flux variability analysis (TFVA) was performed as previously described (Henry et al., 2007) using an open-source module for cobrapy called thermodynamics (https://github.com/dmccloskey/thermodynamics). Blocked reactions were those where the min and max flux was 0, essential reactions were those where the min and max flux were greater than 0, substitutable reactions were those where the min flux was 0 but the max flux was greater than 0, and constrained reactions were those where the min and max flux were the same.

3. Results and discussion

3.1. RapidRIP method development

A RapidRIP method was developed using the same mobile phase, temperature, and column chemistry to the FullRIP method (Fig. 1, Table 1). A shorter column with reduced particle size was used to maintain resolving power at a greatly reduced run-time (see Materials and Methods). A multitude of gradients, flow rates, and flow regimes were tested in order to optimize the method (Fig. S1). The optimized chromatographic parameters are given in the Material and Methods. Flow rate was modulated to allow for faster separation of later eluting compounds and faster column wash and equilibration, while maintaining the ability to retain early eluting compounds and separate hexose and pentose isomers. Percent mobile phase B was modulated to improve the separation of critical pairs, peak shape, and overall sensitivity (Fig. S1, Table S1). Interestingly, it was found that even within a greatly reduced method run time, substantial differences in separation between critical pairs could be obtained by careful tuning of the mobile phase gradient (Fig. S1, Table S1 and S2). Also, compound elution times

Fig. 1. RapidRIP vs. FullRIP chromatography. A comparison of chromatograms obtained from pools of standard mixes ran using the RapidRIP and FullRIP methods. The TIC (A and B), and XICs of lactate (lac-L), pyruvate (pyr), glucose 6-phosphate (g6p), fructose 6-phosphate (f6p), glucose 1-phosphate (g1p), fructose 1-phosphate (f1p), amp, adp, and atp (C and D), and nad(p)(h) (E and F) for the RapidRIP and FullRIP methods, respectively. Inset shows a scaled image of the TIC of the RapidRIP method projected onto the time axis of the FullRIP method.
were evenly distributed and peak widths were minimized in order to maximize the number of transitions that could be analyzed in a given run.

3.2. RapidRIP method validation

The ability of the method to resolve biologically critical isomers was determined. Critical pairs included the hexose and pentose phosphates, mono-, di-, tri-adenine nucleotide phosphates, NAD(P)(H), and citrate/determined. Critical pairs included the hexose and pentose phosphates, 3.2. RapidRIP method validation

RapidRIP method validation

RapidRIP method validation

Table 1

RapidRIP chromatographic gradient. Chromatographic conditions are given in the Section 2.

<table>
<thead>
<tr>
<th>Time</th>
<th>%B</th>
<th>flow_rate</th>
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<tbody>
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<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>0.9</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>1.4</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>1.5</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>1.9</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>2.1</td>
<td>28</td>
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</tr>
<tr>
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<td>0.5</td>
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<tr>
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<tr>
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<td>0.5</td>
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<tr>
<td>4.4</td>
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The RapidRIP method was compared to a previously published 33 min RIP-LC-MS/MS method. It was found that sufficient resolution between critical pairs could be maintained for a majority of the compounds analyzed between the RapidRIP and FullRIP methods (Fig. 1, Tables S2) to allow for comparable quantitation (Fig. 3). For example, the separation between the pentose isomers ribose 5-phosphate and ribulose 5-phosphate was sufficient to achieve baseline separation. A notable compromise in resolution in the reduced method was the separation of glucose 6-phosphate and fructose 6-phosphate, which were not well separated compared to the FullRIP (Fig. 1). However, the unique 199 product ion allows for the direct quantification of glucose 6-phosphate and indirect quantification of fructose 6-phosphate by subtraction of the calculated concentrations as determined from a calibration curve from the 169 and 199 ions.

It was found that both methods were comparable in linearity and sensitivity (Table S4). 54% of the compounds measured with RapidRIP had an LLOQ that was greater than or equal to those measured with FullRIP, and 75% of the compounds measured with RapidRIP had an ULOQ that was greater than or equal to those measured with FullRIP. A decrease in sensitivity and LLOQ but increase in ULOQ was found primarily for early eluting compounds consisting of amino acids, nucleosides and nucleotides. An increase in resolution and LLOQ was found for many later eluting metabolites. The increase in resolution can be explained by the decreased peak width using the RapidRIP method. The overall increase in ULOQ may be attributed to an overall increase in ion suppression due to the number of compounds eluting from the column in a given period of time. This is most noticeable for the early eluting compounds noted above where a loss in sensitivity was also found.

The RapidRIP and FullRIP methods were found to have comparable quantitative accuracy (Fig. 3A-G). A correlation coefficient (Pearson's R) greater than or equal to 0.88 between glog normalized absolute metabolite concentrations (mmol*gDW-1) for all seven strains tested (Fig. 3A-G, Table S7) was found. Interestingly, the peak height ratio correlation coefficients between strains were much less than the absolute metabolite correlation coefficients (Table S7). This indicates that there was sufficient changes in analyte or internal standard peak heights from other components in the sample matrix that were well separated in the FullRIP method that are no longer well separated in the RapidRIP method to make the direct comparison between peak height ratios problematic. However, this also indicates that the use of a calibration curve was sufficient to compensate for the majority of these changes.

The RapidRIP and FullRIP methods were also found to have comparable quantitative precision (Fig. 3H). 61% and 58% of quantified metabolites for all strains had a % RSD less than or equal to 30 for RapidRIP and FullRIP methods, respectively. 7% and 4% of quantified metabolites for all strains had a % RSD greater than 60% RSD for RapidRIP and FullRIP, respectively. The distribution of %RSDs (Fig. 3H), and the percentages of metabolites below 30 and above 60%RSD between both methods indicates that the short method can retain the quantitative precision of the full method.
3.4. Quantification of the intracellular metabolome of seven industrial strains of E. coli

The RapidRIP method was used to quantify the intracellular metabolome of 7 industrial strains of E. coli (Fig. 4, Table S6, see Material and Methods for strains). Consistent with previous literature, the most abundant metabolites in the strains consisted of reduced glutathione, L-glutamate, and ATP (Bennett et al., 2009; Taymaz-Nikerel et al., 2011). Hierarchical clustering (Fig. 4A) reveals that similar to gene expression levels, the levels of intracellular metabolites do not reflect genomic distances between the strains (Monk et al., 2016). The hierarchical clustering is also consistent with how the strains group by Partial Least Squares Differential Analysis (PLS-DA, Fig. 4C). The primary mode of separation between the strains involve differences in glycolytic, pentose phosphate, and TCA cycle intermediates, and the secondary mode of separation include metabolites involved in nucleotide metabolism (Fig. 4D). These differences are discussed in greater detail below.

Physiological ratios are ratios of individual metabolites that often reflect broad physiological states (e.g., energy depletion, redox imbalance, etc..) that are tightly regulated by the cell. Physiological ratios,
including the nitrogen charge, energy charge, glutathione ratio, and
redox ratio, differed between the strains (see methods for ratio defi-
nitions, Fig. 5A). E. coli C and DH5a had the lowest nitrogen and energy
charges due to elevated levels of akg and amp, respectively. Non-
significant differences in the glutathione and redox ratio, but significant
differences in the metabolites that compose those ratios were found.
The conservation of these ratios, but not necessarily the levels of the
individual components may indicate the importance of the glutathione
and redox ratios for maintaining normal aerobic physiology.

The intracellular concentration of 14 amino acids differed between
the strains (Fig. 5B). E. coli DH5a was found to be a poor starting strain
for L-tryptophan production. The intracellular concentrations of L-
tryptophan were significantly lower than the other strains. E. coli
MG1655, C, and W3110 were found to maintain significantly higher
levels of D-aspartate. This is most likely due to utilization of the
Phosphoenolpyruvate Carboxylase (PPC) in MG1655 and W3110
(McCloskey et al., 2016a, 2016b), and overall increased levels of TCA
cycle intermediates in strain C. E. coli MG1655 and W3110 were also
found to have the highest levels of L-arginine. It should be noted that
when compared to the transcript levels or flux predictions of the amino
acid producing pathways (Monk et al., 2016), little correlation between
the absolute metabolite concentrations was found, which indicates the
difficulty in predicting metabolite levels through indirect evidence as is
consistent with previous works (Daran-Lapujade et al., 2007; Hackett
et al., 2016).

Levels of central metabolism intermediates differed vastly between
the strains (Fig. 6). E. coli MG1655, W, and W3110 were found to
maintain significantly lower levels of glycolytic intermediates than other
strains (i.e., g6p, f6p, fdp, 13dpg/23dpg, 2 pg/3 pg, and pep). However,
the levels of pep in W3110 were found to be significantly higher than all other strains. E. coli MG1655 had the highest levels of ribulose and ribose 5-
phosphate (ru5p-D and r5p) compared to the other strains. This most likely contributed to the higher levels of L-
histidine, a downstream product of r5p, in E. coli MG1655.

Based on the data collected here, E. coli C would serve as a good
candidate for aerobic succinate and malate production due to high
endogenous levels of succinate. E. coli C had significantly higher DL-
lactate, succinate, malate, and fumarate concentrations compared to
the other six strains. In addition, the levels of TCA cycle intermediates
citrate and 2-oxoglutarate were among the highest. E. coli C has indeed
previously been successfully used as the base strain for succinate pro-
duction from glucose under aerobic and anaerobic conditions (Balzer
et al., 2013; Jantama et al., 2008; Lin et al., 2005a, 2005b; Sánchez
et al., 2005). Interestingly, E. coli DH5a had the highest levels of citrate,
aconitate, isocitrate, and 2-oxoglutarate. This could indicate altered
regulation or utilization of the TCA cycle in E. coli DH5a.

3.5. Thermodynamic analysis of the seven industrial strains

Change in free energies of reaction (dGr) for each of the industrial
Fig. 5. Physiological ratios (A) and intracellular amino acid levels (B). Selected ratios and metabolite levels that significantly changed are highlighted in the inset. The nitrogen charge (nc) is defined as \((\text{gln-L} + 0.5 \times \text{glu-L}) \times (\text{gln-L} + \text{glu-L} + \text{akg})^{-1}\). The energy charge is defined as \((\text{atp} + 0.5 \times \text{adp}) \times (\text{atp} + \text{adp} + \text{amp})^{-1}\). The glutathione ratio (Gth) is defined as \((\text{gthrd} \times \text{gthox})^{-1}\). The redox ratio is defined as \((\text{nad(p)}h \times (\text{nad(p)}h + \text{nad(p)}h)^{-1}\). Units are the log2 fold change of the median value of each strain to the mean of all 7 strains.

Fig. 6. Absolute metabolite concentrations of central metabolism intermediates for the 7 industrial strains of E. coli. A) Schematic of central carbohydrate metabolism. B) Heatmap of metabolite levels. Units are the log2 fold change of the median value of each strain to the mean of all 7 strains. Selected metabolites that changed significantly are shown in the inset.
strains were calculated and compared in order to identify statistically (i.e., non-overlapping confidence intervals) and biologically (i.e., a change in dG change indicating a change in reaction directionality) significant changes in reaction thermodynamics between the strains (Table S8). Of the 475 reactions with satisfactory measured metabolomics and free energy of formation coverage (see Methods), between 22 and 58 statistically different reactions were found between the strains, between 4 and 17 biologically different reactions were found between the strains, and between 0 and 4 statistically and biologically different reactions were found between the strains (Fig. 7, Table S9).

Thermodynamics analysis revealed differences in the thermodynamic potential to push carbon towards glycogen biosynthesis instead of more economically valuable carbon endpoints between the strains. Biologically and statistically significant differences were found between glucose 1-phosphate adenyltransferase (GLGC, EC 2.7.7.27) in E. coli C and all other strains except E. coli W and W3110 (Fig. 7). E. coli C had the highest levels of the glycogen precursor ADP-glucose, which leads to the thermodynamic differences. ADP-glucose (adpglc) is formed from glucose 1-phosphate via GLGC. Increased expression of glgC or mutations in glgC that increase GLGC activity have been shown to accumulate glycogen (Ballicora et al., 2003; Eydallin et al., 2007; Ghosh et al., 1992; Leung et al., 1986). No significant differences in the transcriptomic profiles of glgC in E. coli C were found and E. coli C is not known to harbor any unique mutation in the glgC gene, indicating that the elevated levels of adpglc could be due to kinetic factors.

Thermodynamics analysis also revealed that E. coli BL21 can be feasibly thermodynamically. Metrics for sensitivity, resolution, linearity, accuracy, and precision was determined and compared to a FullRIP method. All metrics were found to be comparable with a few minor compromises as noted in the main text. The RapidRIP method significantly accelerates metabolic characterization compared to existing methods. Combined with high-throughput cultivation methods this allows using metabolomics as a routine tool for characterizing the large-numbers of engineered or evolved microbial strains that modern cloning, genome editing and laboratory evolution approaches create.

4. Conclusion

In this study, a RapidRIP method capable of quantifying over 100 metabolites in less than 5 min was described. The method is capable of analyzing 327 samples per day (or 2289 samples per week). Including QC, calibrator, and carryover check samples, this amounts to approximately 1000 strains that can be screened per week on a single instrument. Metrics for sensitivity, resolution, linearity, accuracy, and precision was determined and compared to a FullRIP method. All metrics were found to be comparable with a few minor compromises as noted in the main text. The RapidRIP method significantly accelerates metabolic characterization compared to existing methods. Combined with high-throughput cultivation methods this allows using metabolomics as a routine tool for characterizing the large-numbers of engineered or evolved microbial strains that modern cloning, genome editing and laboratory evolution approaches create.

In order to demonstrate the applicability of RapidRIP for characterizing strain differences, od was used to quantify the metabolome of 7 industrial strains of E. coli during aerobic growth on glucose. Major differences in central, amino acid, nucleotide, energy, and redox metabolism metabolite levels were found. These differences translated to statistically significant differences in reaction thermodynamics; several of which were also found to be biologically significant through change
in reaction directionality. Knowledge of these differences provides researchers with valuable information when choosing which strain to use as host for a particular chemical production process. For example, researchers should not be dissuaded from using the BL21 strain based on theoretical predictions of compound yield derived from genomic information alone because the thermodynamics of the PPP in the absence of the pgl gene are such that flux and levels of NADPH are not significantly altered.

Acknowledgements

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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.2018.04.009.

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