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Leveraging host metabolism for bisdemethoxycurcumin production in *Pseudomonas putida*

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**ABSTRACT**

*Pseudomonas putida* is a saprophytic bacterium with robust metabolisms and strong solvent tolerance making it an attractive host for metabolic engineering and biomediation. Due to its diverse carbon metabolisms, its genome encodes an array of proteins and enzymes that can be readily applied to produce valuable products. In this work we sought to identify design principles and bottlenecks in the production of type III polyketide synthase (T3PKS)-derived compounds in *P. putida*. T3PKS products are widely used as nutraceuticals and medicines and often require aromatic starter units, such as coumaroyl-CoA, which is also an intermediate in the native coumarate catabolic pathway of *P. putida*. Using a randomly barcoded transposon mutant (RB-TnSeq) library, we assayed gene functions for a large portion of aromatic catabolism, confirmed known pathways, and proposed new annotations for two aromatic transporters. The 1,3,6,8-tetrahydroxynapthalene synthase of *Streptomyces coelicolor* (RppA), a microbial T3PKS, was then used to supply coumaroyl-CoA for the curcuminoid synthase (CUS) of *P. putida*. We identified that accumulation of coumaroyl-CoA in this pathway results in extended growth lag times in *P. putida*. Deletion of the second step in coumarate catabolism, the enoyl-CoA hydratase-lyase (Ech), resulted in increased production of the type III polyketide bisdemethoxycurcumin.

1. Introduction

Secondary metabolites of fungi, plants, and bacteria have long been used as medicines and supplements (Hewlings and Kalman, 2017). Compounds such as naringenin, raspberry ketone, resveratrol, and curcumin are widely used nutraceuticals and are biosynthesized through similar pathways (Heller and Hahlbrock, 1980; Katsuyama et al., 2008; Schanz et al., 1992; Smith, 1996). Commercially, these chemicals are either extracted directly from plants or produced synthetically, as in the case of raspberry ketone (Smith, 1996). Renewable microbial production of these compounds will decrease reliance on agriculture and fossil fuel-derived chemical synthesis. The biosynthesis of these compounds (naringenin, raspberry ketone, resveratrol, and curcumin) relies on a class of enzymes called type III polyketide synthases (T3PKSs). T3PKSs carry out iterative Claisen condensation reactions typically with coenzyme A (CoA)-based starter and extender units (Yu et al., 2012). In the case of the 1,3,6,8-tetrahydroxynapthalene synthase of *Streptomyces coelicolor* (RppA) the starter and extender units are simply malonyl-CoA, while in many plant T3PKSs the starter unit is a phenylpropanoyl-CoA thioester, usually derived from ferulate, coumarate, or cinnamonate (Izumikawa et al., 2003; Wakimoto et al., 2012).

Coumarate and ferulate are components of lignin found in lignocellulosic hydrolysate (LH), which has been proposed for use as a renewable feedstock for biocatalysis (Jönsson et al., 2013; Lawther and Sun, 1996). Characteristics such as high solvent tolerance and diverse carbon metabolisms are essential for microbes to be used in LH valorization. However, these robust traits are lacking in commonly used model organisms, such as *Escherichia coli*, hindering progress toward making LH a viable feedstock (Mills et al., 2009). Rather than developing these characteristics in a microorganism *de novo*, a clear alternative is to source
a microbe with the desirable traits already available to it. The saprophytic bacterium *Pseudomonas putida* has long been studied for its ability to catabolize aromatic compounds and withstand solvents, making it an attractive host for LH upcycling (Guarnieri et al., 2017; Linger et al., 2014; Nozaki et al., 1963).

In this work we sought to leverage the native catabolism of *P. putida* KT2440 for use in the biosynthesis of a plant T3PKS product from coumarate. RppA of *S. coelicolor* was first expressed to determine production conditions conducive to T3PKS product accumulation. Using a randomly barcoded transposon mutant (RB-TnSeq) library of *P. putida*, we assayed for genes involved in the catabolism of coumarate and seven other related aromatic compounds. We then found that accumulation of coumaroyl-CoA by the activity of Fcs was toxic to *P. putida*. The native feruloyl/coumaroyl-CoA synthetase (Fcs) of *P. putida* was then used to produce the coumaroyl-CoA starter unit to the curcuminoid synthase feruloyl/coumaroyl-CoA synthetase (Fcs) of *S. coelicolor* from the chromosome and plasmid-based expression of *fcs* from the chromosome and plasmid-based expression of *fcs*

2. Results

2.1. RppA as a screen for optimal T3PKS production conditions

The tetrahydroxynaphthalene synthase of *Streptomyces coelicolor* was recently applied as a biosensor for malonyl-CoA concentrations in several hosts including *P. putida* (Yang et al., 2018). We sought to express this protein from the broad host range pBADT vector to assay culture conditions for increased product accumulation in *P. putida*. RppA was initially codon optimized for expression in *P. putida* and cloned into the construct pBADT-rppA-OW. We then constructed two more plasmids, one with the complete *rppA* cloned from the *S. coelicolor* genome (pBADT-rppA-NW) and another with a 3’ truncation of 75 base pairs (pBADT-rppA-NT) as this had been described previously to increase enzymatic activity (Iizumikawa et al., 2003).

Since the product of RppA, 1,3,6,8-tetrahydroxynaphthalene, spontaneously oxidizes to the red pigment flavilon, we used a colorimetric assay to determine how glucose concentrations affect the production of T3PKS products (Fig. 2A). Concentrations of glucose ranging from 0 - 400 mM supplemented into LB medium were tested, and the production of flavilon was measured by absorbance at 340 nm, as previously reported (Yang et al., 2018). Unexpectedly, the *rppA* expression vectors using the native *S. coelicolor* codons produced more flavilon than the *P. putida* codon optimized variant (Fig. 2B). In all three constructs tested, there was an increase in the accumulation of flavilon in cultures containing greater than 25 mM glucose and accumulation of flavilon appeared to plateau at ~100 mM glucose (Figs. 2B and S4). To validate the observed red compound was flavilon, we extracted, purified, and obtained an 1H-NMR spectrum for the red product using established methods (Figs. S5A and S5B) (Gross et al., 2006; Soga, 1982). The final yield from 100 mL of culture was ~6.5 mg.

Following this result, we sought to identify if increased protein abundance was the cause for increased flavilon production. When RppA was quantified using LC-MS, we observed an increase in its relative abundance for all variants when 100 mM glucose was supplemented to the medium. The abundance of RppA also was highest in the strains expressing the native genomic sequence of *rppA* (Fig. 2C).

2.2. Functional genomics to validate aromatic catabolisms of *P. putida*

While aromatic catabolism has been extensively studied in *P. putida*, essential genes implicated in these pathways have been described as recently as 2019 (Price et al., 2019). The genes involved in the first steps of coumarate catabolism reside in an operon with a putative acyl-CoA dehydrogenase (*pp_3354*) and a putative beta-ketothiolase (*pp_3355*), which have been proposed to be involved in an alternative catabolic pathway (Overhage et al., 1999). As functional redundancy in coumarate catabolism could result in loss of the type III polyketide precursor, coumaroyl-CoA, we sought to identify any pathways that could potentially impact product titers. To assay for genes involved in coumarate and related aromatic metabolisms, we grew a randomly barcoded transposon mutant (RB-TnSeq) library of *P. putida* KT2440 in minimal medium with a variety of different aromatic compounds often found in LH (p-coumarate, ferulate, benzoate, p-hydroxybenzoate, protocatechuate, vanillin, vanillinate, phenylacetate) and glucose as sole carbon sources. The fitness of each gene was calculated by comparing the abundance of barcodes before versus after growth selection, using barcode sequencing (BarSeq) (Rand et al., 2017; Wetmore et al., 2015). Negative values indicate that the gene was important for growth in that condition.

The results of the RB-TnSeq assay validated that the primary route for flavilon production is through the feruloyl/coumaroyl-CoA synthetase (Fcs) and the enoyl-CoA hydratase lyase (Ech) (Fig. 3 and Fig. S1). The genes in the proposed secondary pathway of coumarate catabolism, *PP_3354* and *PP_3355*, had no significant fitness phenotype, indicating that these genes are likely not necessary for coumarate or ferulate catabolism (Plaggenborg et al., 2003).

**Fig. 1.** Diagram of the engineered *P. putida* strain used to produce bisdemethoxycurcumin. Fcs is the feruloyl/coumaroyl-CoA synthetase native to *P. putida* KT2440. Ech is the native enoyl-CoA hydratase-lyase which carries out the second step in coumarate catabolism and was knocked out in our production host. CUS is the curcuminoid synthase from *O. sativa*. BDC is the final curcuminoid product, bisdemethoxycurcumin.
Of all the known reactions depicted in the map of aromatic catabolism (Fig. 3), we observed significant negative fitness values for all but three of their corresponding genes: catA-I, catA-II, and pcaC. Even though the fitness score was higher than our cutoff at −1.4, catA-I had a significant t-score of 6.2 when grown on benzoate. This reflects previous work demonstrating CatA-I is the preferred catechol 1,2-dioxygenase, while CatA-II acts as a “safety valve” to handle high intracellular concentrations of catehol. It was also demonstrated that both catA-I and catA-II need to be deleted to abolish growth on benzoate, and this likely explains why the fitness value for catA-I was above our cut-off (Jiménez et al., 2014). In the case of pcaC, we noticed that there was a strong phenotype (fitness < −2.0), but the significance fell below our cutoff in all conditions tested (t-score < 4.0). This is likely due to the low frequency of transposon insertions into this gene in the library (n = 4).

While our results heavily support the current models of aromatic metabolism in P. putida, our data also indicated that some gene annotations should be revised. PP_3272 is currently annotated as encoding an acetate permease (Kanehisa, 2019; Kanehisa et al., 2019; Kanehisa and Goto, 2000). We observed that PP_3272 had a significant phenotype when grown on phenylacetate (Fig. 3). Given these data and previously described homology to other systems (Jiménez et al., 2002), PP_3272 should be reannotated as the phenylacetate transporter (phaJ). The PP_1376 gene is annotated as encoding a 4-hydroxybenzoate transporter (Kanehisa and Goto, 2000); however, we only observed a fitness detriment for this gene with protocatechuate as the sole carbon source (Fig. 3). Because of this, PP_1376 should be reannotated as a protocatechuate transporter.

2.3. Accumulation of coumaroyl-CoA is toxic to P. putida

The first step in the biosynthetic pathway for bisdemethoxycurcumin is the activation of coumarate with coenzyme A (CoASH) (Fig. 1). Because Pseudomonas putida KT2440 natively produces coumaroyl-CoA during coumarate catabolism, we knocked out the subsequent gene in the native catabolic pathway, ech, to prevent P. putida from consuming this necessary precursor (Fig. 1) (Jiménez et al., 2002). Initial production experiments in Δech strains overexpressing fcs and CUS from a synthetic operon resulted in an extended lag phase (data not shown). To determine the cause, we overexpressed fcs alone under control of the arabinoxyl-inducible araBAD promoter (PBAD) in the presence and absence of coumarate. Increasing the inducer concentration resulted in increased lag times only when coumarate was present in the medium (Figs. 4A and S6). This suggested that the coumaroyl-CoA intermediate is toxic to P. putida.

To determine if coumaroyl-CoA concentrations are elevated in cultures expressing fcs, cultures carrying pBADT-fcs were induced with L-arabinose. After a 7 h growth period, 5 mM coumarate was supplemented to the medium. Following supplementation, growth was stunted and remained relatively constant over the course of 11 h. The concentration of coumaroyl-CoA was highest in samples 1 h after coumarate was supplemented into the medium; this was observed regardless of the ech genotype (Fig. 4B). We therefore sought to minimize the burden of this intermediate by relying on the native chromosomal expression of fcs in future experiments.

2.4. Production of bisdemethoxycurcumin

In order to produce bisdemethoxycurcumin in P. putida, we constructed the biochemical pathway outlined in Fig. 1. Exogenously added coumarate is activated by the native feruloyl/coumaroyl-CoA synthetase of P. putida (Fcs), then two resultant coumaroyl-CoA molecules are condensed with malonyl-CoA by the curcuminoid synthase of O. sativa (CUS) to yield bisdemethoxycurcumin (Katsuyama et al., 2007b). The CoA synthetase, fcs, was expressed from its native chromosomal locus, while CUS was expressed from the pBADT plasmid and induced with L-arabinose (Bi et al., 2013).

Our initial production strategy was to induce CUS until the cultures reached stationary phase. Then the cultures were pelleted and resuspended in fresh LB medium supplemented with 5 mM coumarate. These samples were then incubated for another 72 h. A similar approach had been used successfully in E. coli (Katsuyama et al., 2007a); however, our titers were less than 0.5 mg/L (Fig. S2). Given that bisdemethoxycurcumin is insoluble in water (Javeri and Chand, 2016), a 10% v/v oleyl alcohol overlay was used to extract the product as the fermentation progressed. Production levels were low (approximately 0.1 mg/L) in P. putida Δech when the medium was supplemented with 10 mM coumarate, likely due to the toxicity of coumaroyl-CoA (Fig. 5). Supplementation with 5 mM coumarate resulted in a ~5-fold increase in

Fig. 2. Flavivolin production as a reference for T3PKS activity. (A) Diagram of the pathway to the red pigment, flavivolin, from RppA and subsequent spontaneous oxidation. (B) Absorbance measurements at 340 nm of supernatants from cells expressing RppA variants in LB containing different concentrations of glucose. Error bars indicate the standard deviation of three replicates. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
Fig. 3. Overview of aromatic catabolism in P. putida KT2440. The colored and labelled compounds depicted were fed as sole carbon sources to the barcoded transposon library. Fitness values for each gene are the average of 2 replicate RB-TnSeq assays, and are colored corresponding to the carbon source (gray: benzoate, red: coumarate, blue: 4-hydroxybenzoate, light green: ferulate, dark green: vanillate, purple: vanillin, yellow: protocatechuate, pink: phenylacetate). For reactions where multiple genes are necessary, i.e. enzyme complexes, the fitness values for each gene involved in the reaction were averaged. *The t-score for pcaC was insignificant (|t| < 4.0) and was excluded from our analysis. **Fitness values for these genes were mild (fitness > 2.0) and excluded. ***Fitness value corresponds to paaJ. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
bisdemethoxycurcumin titers in the *P. putida* Δ*ech* strain relative to wild-type (Fig. 5).

**3. Discussion**

*Pseudomonas putida* is among the most well studied saprophytic bacteria. Its diverse metabolisms enable it to catabolize a wide variety of complex carbon sources, including lignocellulosic hydrolysate (Wang et al., 2019). The robust catabolic pathways of *P. putida*, while useful for producing valuable molecules from diverse carbon sources, can also serve as an obstacle to achieving high product titers as it can often metabolize the desired products (Thompson et al., 2019b). Given recent advances in gene editing techniques (Aparicio et al., 2019, 2018; Cook et al., 2018; Martínez-García and de Lorenzo, 2011; Wirth et al., 2019) and our ability to rapidly assay for gene function with transposon site sequencing (Price et al., 2018; Rand et al., 2017; Wetmore et al., 2015), engineering non-model hosts like *P. putida* for industrial applications has become less challenging.

Using RB-TnSeq mutant fitness assays we were able to rapidly confirm entire pathways of aromatic catabolism (Figs. 3 and S1). The genes downstream of *fcs*, *PP_3354* and *PP_3355* previously described as a possible alternative route for coumarate/ferulate catabolism (Jiménez-C1902; Overhage et al., 1999; Priefert et al., 2001), showed no significant fitness detriment on any of the carbon sources tested. These genes may be structural remnants of a β-oxidation pathway that eventually evolved into the coumarate/ferulate pathway requiring *fcs*, *ech*, and *vdh* (Jiménez et al., 2002; Overhage et al., 1999; Priefert et al., 2001). We then proposed revised annotations of two genes required for transport of the aromatic compounds, phenylacetate (*PP_3272*) and protocatechuate (*PP_1376*), an important plant hormone and lignin metabolite respectively (Wightman and Lighty, 1982). There is a large amount of information in these data encompassing regulatory and structural genetic elements that could be useful to engineers and biologists.

Heterologous expression of bacterial T3PKSs, including the tetrahydroxynaphthalene synthase of *S. coelicolor* (RppA), has previously been demonstrated in *P. putida* KT2440 (Gross et al., 2006; Yang et al., 2018). Using variants of *rppA*, we were able to rapidly screen type III polyketide production conditions. Expressing the codon optimized variant we created in this study, *rppA*-OW, resulted in less flaviloin production and less protein production than the native codon variants *rppA*-NW and *rppA*-NT. It is possible that there are some factors affecting heterologous protein expression that are not sufficiently accounted for in current codon optimization algorithms (Cambray et al., 2018). However, we demonstrated in all our constructs that increasing the glucose concentration had a considerable effect on the production of flaviloin (Figs. 2 and S4).

Higher flaviloin accumulation with increased glucose concentrations could be due to increased flux to malonyl-CoA, a known limiting reactant to the biosynthesis of plant T3PKS products (Katsuyama et al., 2008; Zang et al., 2019), or due to increased functional protein expression. As the relative abundance of RppA increased when the culture was grown in...
4.1. Media, chemicals, and culture conditions

In the presence of 100 mM glucose, we hypothesize this likely contributed to the increased flavinol titer observed in this condition (Fig. 2B and C). The exact cause for the increase in protein abundance requires more detailed investigation. These T3PKS “sensors” have broad utility in both rapidly assaying culture conditions, as described here, and as high-throughput screens of genetic libraries for increased malonyl-CoA accumulation (Yang et al., 2018). Future work could employ these sensors to screen for increased intracellular malonyl-CoA concentrations from a complex growth medium like LH.

To provide the coumaroyl-CoA substrate for the bisdemethoxycurcumin T3PKS, CUS, we sought to use the native CoA synthetase (Fcs) of P. putida. Plasmid-based induction of fcs expression in the presence of coumarate, however, resulted in an increase in lag times due to the buildup of the toxic coumaroyl-CoA intermediate (Figs. 4A, 4B, and S6). Neither the accumulation of coumaroyl-CoA nor the resultant growth inhibition seemed to be significantly affected by the genetic presence of ech (Fig. 4B). The reduction in intracellular coumaroyl-CoA concentrations following the addition of coumarate was also not dependent on the presence of ech (Fig. 4B). This reduction in thioester concentrations may be the result of nonspecific thioesterase activity, or spontaneous hydrolysis of coumaroyl-CoA.

The toxicity of hydroxycinnamate thioesters has been reported in Acinetobacter baylyi following disruptions in the gene encoding its enoyl-CoA hydrolase lyase, and it was observed in E. coli expressing the A. baylyi fcs homolog in the presence of coumarate (Parke and Ornston, 2004). This toxicity could have been limiting other systems using bacterial coumaroyl-CoA synthetases, but the defective growth phenotype may not have been observed due to differences in experimental design (Park et al., 2009; Santos et al., 2011). The exact cause for coumaroyl-CoA toxicity remains unclear and will be the subject of future investigations.

To engineer P. putida for bisdemethoxycurcumin production, we deleted the native enoyl-CoA hydratase lyase (ech) responsible for the conversion of coumaroyl-CoA to acetyl-CoA and p-hydroxybenzaldehyde. In order to relieve some of the observed coumaroyl-CoA toxicity, we relied on the native genomic copy of fcs instead of a plasmid-based system. We demonstrated that native expression of fcs generates sufficient coumaroyl-CoA for curcuminoid synthase (CUS). Extraction of the product during growth using an oleyl alcohol overlay also significantly enhanced titers (Figs. S2 and 5). In the final P. putida production strain, we achieved production of bisdemethoxycurcumin at titers of 2.15 mg/L (Fig. 5).

This work is a significant first step towards the production of plant T3PKS-derived compounds in P. putida, but several issues remain to be addressed. In particular, our final bisdemethoxycurcumin titer of 2.15 mg/L is far lower than the 91.3 mg/L titer first described in E. coli (Katsuyama et al., 2008). Several methods have been proposed to enhance the production of curcuminoids and similar T3PKS derived compounds in microbial hosts. In one such approach, the metabolic burden of product, protein, and plasmid DNA synthesis was spread across several microbial strains in a synthetic co-culture (Yang et al., 2018). Since phenylpropanoid overproducing strains of P. putida have been described (Nijkamp et al., 2007, 2005), a co-culture method could be explored for the biosynthesis of plant T3PKS products in this host. It is also quite clear that more extensive pathway balancing will be required to mitigate the intermediate toxicity we have observed. As we continue to understand more about the metabolism of P. putida and learn to engineer it more effectively, this host will become an increasingly attractive chassis for renewable chemical biosynthesis.

4. Methods

4.1. Media, chemicals, and culture conditions

General E. coli cultures were grown in Luria-Bertani (LB) Miller medium (BD Biosciences, USA) at 37 °C, while P. putida was grown at 30 °C.

MOPS minimal medium was used where indicated and comprised of the following: 32.5 μM CaCl2, 0.29 mM K2SO4, 1.32 mM KH2PO4, 8 μM FeCl2, 40 mM MOPS, 4 mM tricine, 0.01 mM FeSO4, 9.52 mM NH4Cl, 0.52 mM MgCl2, 50 mM NaCl, 0.03 μM (NH4)6Mo7O24, 4 μM H2B2O3, 0.3 μM CoCl2, 0.1 μM CuSO4, 0.8 μM MnCl2, and 0.1 μM ZnSO4 (Labauve and Wargo, 2012). Cultures were supplemented with kanamycin (50 mg/L, Sigma Aldrich, USA) when indicated. Technical grade oleyl alcohol was acquired from Alfa Aesar (Alfa Aesar, Thermo Fisher Scientific). Coenzyme A (lithium salt) was purchased from CoA La Biosciences (CoA La Biosciences, USA). All other compounds were purchased through Sigma Aldrich (Sigma Aldrich, USA). Construction of P. putida deletion mutants was performed as described previously (Thompson et al., 2019a).

4.2. Strains and plasmids

Bacterial strains and plasmids used in this work are listed in Table 1. All strains and plasmids created in this work are available through the public instance of the JBEI registry https://public-registry.jbei.org. All plasmids were designed using Device Editor and Vector Editor software, while all primers used for the construction of plasmids were designed using J5 software (Chen et al., 2012; Ham et al., 2012; Hillson et al., 2012). Plasmids were assembled via Gibson Assembly using standard protocols (Gibson et al., 2009), or Golden Gate Assembly using standard protocols (Engler et al., 2008). Plasmids were routinely isolated using the Qiagen Spin Miniprep kit (Qiagen, USA), and all primers were purchased from Integrated DNA Technologies (IDT, Coralville, IA).

4.3. Plate based growth assays

Growth studies of bacterial strains were conducted using microplate reader kinetic assays. Overnight cultures were inoculated into 10 mL of LB medium from single colonies, and grown at 30 °C. These cultures were then diluted 1:100 into 500 μL of LB medium with appropriate concentrations of arabinose and p-coumarate in 48-well plates (Falcon, 353072). Plates were sealed with a gas-permeable microplate adhesive film (VWR, USA), and optical density and fluorescence were monitored for 48 h in a Biotek Synergy 4 plate reader (BioTek, USA) at 30 °C with fast continuous shaking. Optical density was measured at 600 nm. The amount of time necessary for the culture to reach an OD600 of 0.16 was defined as the lag time.

4.4. HPLC detection of bisdemethoxycurcumin

HPLC analysis was performed on an Agilent Technologies 1200 series liquid chromatography instrument coupled to a Diode Array Detector (Agilent Technologies, USA). Compounds were separated at a constant flow rate of 0.4 mL/min over a Kinetic C18 column (2.6 μm diameter, 100 Å particle size, dimensions 100 x 3.00 mm, Phenomenex, USA) held at 30 °C.

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<thead>
<tr>
<th>Strain</th>
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<td>Grant et al. (1990)</td>
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<tr>
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<td>Novagen</td>
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<tr>
<td>P. putida KT2440</td>
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at 50 °C. The mobile phase consisted of H₂O + 0.1% trifluoroacetic acid (A) and acetonitrile + 0.1% trifluoroacetic acid (B). Separation was performed using the following gradient method: 0–3 min 95% A, 3–15 min 95-5% A, 15–17 min 5% A, 17–17.5 min 5–95% A, 17.5–20 min 95% A. The presence of bisdemethoxycurcumin was monitored and quantified at 440 nm.

4.5. RB-TnSeq experiments and analysis

BarSeq-based experiments utilized the P. putida RB-TnSeq library, JBEI-1, which has been described previously (Thompson et al., 2019a). An aliquot of JBEI-1 was thawed on ice, diluted into 25 mL of LB medium supplemented with kanamycin and grown to an OD₆₀₀ of 0.5 at 30 °C. An aliquot of JBEI-1 was thawed on ice, diluted into 25 mL of LB medium supplemented with kanamycin and grown to an OD₆₀₀ of 0.5 at 30 °C. Three 1 mL aliquots of the library were pelleted and stored at −80 °C to later serve as the t₀ of gene abundance. Libraries were then washed in MOPS minimal medium and diluted 1:5 in MOPS minimal medium with 10 mM p-coumarate, ferulate, benzoate, p-hydroxybenzoate, protocatechuic acid, vanillin, vanillate, phenylacetate, or D-glucose. Cells were grown in 600 μL of medium in 96-well deep well plates (VWR). Plates were sealed with a gas-permeable microplate adhesive film (VWR, USA), with shaking at 700 rpm. Two 600-μL samples were combined, pelleted, and stored at −80 °C until analysis by BarSeq, which was performed as previously described (Rand et al., 2017; Wetmore et al., 2015). All fitness data are publicly available at http://fit.genomics.lbl.gov.

4.6. Curcuminoid production

For production of bisdemethoxycurcumin without an overlay, an overnight culture of P. putida KT2440 ΔrppA + pBADT-CUS was diluted 1:100 into 5 mL of LB supplemented with 50 mg/L kanamycin, 1% v/v L-arabinose, and 100 mM glucose. The culture was grown to stationary phase over 12 h then pelleted in a centrifuge at 5000×g for 5 min. The cell pellets were resuspended in 2 mL of fresh LB with 50 mg/L kanamycin, 0.5% L-arabinose, 100 mM glucose, and 5 mM coumarate. The culture was allowed to proceed for 72 h.

For experiments employing an overlay, overnights of P. putida harboring pBADT-CUS were diluted 1:100 into 25 mL of fresh LB supplemented with 50 mg/L kanamycin, and 100 mM glucose. Arabinose and coumarate were added at the beginning of the fermentation at concentrations indicated. A 2.5 mL overlay of oleyl alcohol was added to the culture after 72 h. For cultures expressing rppA variants in LB, the supernatants were too opaque with red product and needed to be diluted 1:5 in fresh LB for accurate absorbance measurements. Supernatants of strains cultured in minimal medium were not diluted before absorbance measurements.

Samples for intracellular targeted proteomic analysis were grown for 48 h in 5 mL LB supplemented with 0 mM or 100 mM glucose. Then, 2 mL of the culture were then pelleted by centrifugation, the supernatant was decanted, and the pellets were stored at −80 °C. Proteins were extracted and analyzed using a variation of a previously-described workflow (Chen et al., 2019).

4.7. Curcuminoid extraction

For cultures lacking an overlay, 0.5 mL of culture was acidified to pH 3 with 3 N HCl. Bisdemethoxycurcumin was then extracted with an equal volume of ethyl acetate. 250 μL of the ethyl acetate layer was removed and the solvent was allowed to evaporate overnight. The dried samples were then resuspended in 50 μL of acetonitrile for analysis with HPLC-DAD.

For cultures with an overlay, the cultures were acidified to pH 3 with 3 N HCl. Acidified cultures were then pelleted in a centrifuge and the oleyl alcohol overlays were removed. To quantify bisdemethoxycurcumin, 100 μL of the extracted overlays were added to a black, clear bottom 96-well plate and absorbance was measured at 425 nm in a Biotek Synergy 4 plate reader (BioTek, USA). A standard curve was made with bisdemethoxycurcumin standards dissolved in oleyl alcohol (Fig. S3).

4.8. Flaviolin production and targeted proteomic analysis

Colonies of P. putida KT2440 strains carrying pBADT-rppA-NW, pBADT-rppA-NT, and pBADT-rppA-OY were used to inoculate LB or MOPS minimal medium with 50 mg/L kanamycin and cultured overnight. The overnight culture was then diluted 1/100 into fresh medium with 0.2% w/v L-arabinose, 50 mg/L kanamycin, and 400, 200, 100, 50, 25, 12.5, 6.25 or 0 mM glucose. Cultures were conducted in 24-well deep-well plates and allowed to proceed for 48 h. Cultures were then pelleted in a centrifuge at 5000×g for 5 min. Supernatants were removed, aliquoted into a 96-well black clear bottom plate, and the absorbance was measured at 340 nm in a Biotek Synergy 4 plate reader (BioTek, USA).

For cultures expressing rppA variants in LB, the supernatants were too opaque with red product and needed to be diluted 1:5 in fresh LB for accurate absorbance measurements. Supernatants of strains cultured in minimal medium were not diluted before absorbance measurements.

An overnight culture of P. putida KT2440 carrying pBADT-rppA-NT was diluted 1:100 into 100 mL of LB supplemented with 25 mg/L kanamycin, 0.2% w/v L-arabinose, and 100 mM glucose. The culture was shaken for 48 h at 30 °C in a 500 mL baffled Erlenmeyer flask. Following fermentation, the red supernatant was removed, acidified with 10 mL 1 N HCl, and extracted twice with equal volumes of ethyl acetate. The combined organic phase was evaporated leaving a black solid, which was then dissolved in ethyl acetate and methanol (7:3). The extract components were then separated using preparative thin layer chromatography (TLC, silica gel). The red band was isolated from the TLC plate, extracted with methanol, and filtered. The methanol was evaporated in vacuo leaving dark red solid with a yield of ~6.5 mg. The identity of the flaviolin was then validated with 1H-NMR. 1H-NMR (400 MHz, CD₂OD) δ 6.99 (s, 1 H), 6.47 (s, 1 H), 5.58 (s, 1 H) (Figs. S5A and S5B) (Snyder et al., 2009).
4.10. Synthesis of coumaroyl-CoA standard

Coumaroyl-Coenzyme A (2) was synthesized in two steps according to Scheme 1. S-phenyl (E)-3-(4-hydroxyphenyl)prop-2-enethioate (1) was synthesized according to previous literature (Hori et al., 2012). 1-(3-Dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (WSCD-HCl, 1.48 g, 7.3 mmol), 1-hydroxybenzotriazole (HOBT, 1.12 g, 7.3 mmol), and 4-hydroxycinnamic acid (1 g, 6.1 mmol) were dissolved in DCM (100 mL) and stirred for 1 h at room temperature. After the solvent was removed in vacuo, water and dichloromethane (DCM) were added to the mixture. The organic layers were combined, dried over Na2SO4, and evaporated. The product was purified with silica-gel column chromatography and eluted with DCM to yield S-phenyl (E)-3-(4-hydroxyphenyl)prop-2-enethioate as a white solid (1, 468 mg, 30%).

To synthesize coumaroyl-CoA (2), coenzyme A lithium salt (7.7 mg, 10 μmol) was dissolved in a solution of saturated sodium bicarbonate (750 μL) which had been pre-chilled to 4 °C. S-phenyl (E)-3-(4-hydroxyphenyl)prop-2-enethioate (30 mg, 117 μmol) was added to the solution. The solution was mixed for 16 h at 4 °C then quenched via the addition of 6 M HCl to bring the pH of the solution to ~2. The mixture was extracted with ethyl acetate (2 × 2 mL), then coumaroyl-CoA was purified from the remaining aqueous phase via preparatory HPLC.

Coumaroyl-CoA was purified using an Agilent 1260 series preparatory HPLC system equipped with a 900 μL sample loop and a UV detector coupled to a fraction collector. Compounds were separated over an Agilent Zorbax SB-C18 preparatory column (9.4 × 50 mm, 5 μm particle size) using a mobile phase composed of 10 mM ammonium formate, pH 4.5 (solvent A) and methanol (solvent B) using the following method:

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>%A</th>
<th>%B</th>
<th>Flow rate (mL/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>95</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>95</td>
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<td>95</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>95</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>16</td>
<td>95</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

The fraction collector was programmed to collect peaks absorbing at a wavelength of 260 nm and that eluted between 3.6 and 4.6 min. The fractions containing coumaroyl-CoA were identified by direct infusion onto an Applied Biosystems 4000 QTRAP mass spectrometer system operating with the following parameters: Q1 MS mode, scan range 100–1000 m/z, declustering potential: 70, Entrance potential: 10, Collision cell exit potential: 10. Coumaroyl-CoA was detected in multiple reaction monitoring (MRM) mode by monitoring the following transition: 914.16 m/z → 407.16 m/z using a collision energy of 47.8 V. Data was imported into Skyline targeted mass spectrometry environment (v. 3.7.0 11317) and peaks were integrated using Skyline’s embedded integration function. Coumaroyl-CoA was quantified relative to a standard curve that was generated by calculating the linear regression of 3 individual injections of each concentration within the standard curve (R² = 0.9982).

4.11. LC-MS/MS analysis of intracellular coenzyme a esters

P. putida KT2440 and P. putida Aceh cells carrying pBADT-fcs were cultured overnight. Cultures were inoculated 1:100 into 25 mL LB supplemented with 100 mM glucose and 0.2% w/v L-arabinose. Cells were cultured at 30 °C for 7 h then coumaroyl-CoA was added to a final concentration of 5 mM 10 mL of culture were taken at hours 8, 11, and 19 and pelleted in a centrifuge. Cell pellets were resuspended in 1 mL ice cold methanol and stored at −80 °C until workup.

Coenzyme A esters were extracted as follows: to the 1 mL methanol resuspensions, 0.5 mL of ice cold LC grade water and 0.25 mL ice cold LC chloroform. Samples were vortexed to mix after each addition. Samples were then centrifuged at maximum speed for 2 min to promote phase separation, after which 0.5 mL of the top aqueous phase was removed and transferred to an Amicon 3 kDa molecular weight cutoff centrifuge filter (Sigma Aldrich, USA). Extracts were filtered by spining in a benchtop centrifuge at 4 °C for 90 min at 13000 g. The flow through was lyophilized for 24 h to concentrate the sample. Lyophilized fractions were resuspended in 0.1 mL of ice cold 60:40 (v/v) LC grade acetonitrile: LC grade water, and 35 μL of the aqueous layer was removed for LC-MS/MS analysis.

CoA extracts were analyzed using an Applied Biosystems 4000 QTRAP mass spectrometer coupled to an Agilent 1100–1200 series HPLC. Compounds were separated over a Phenomenex Kinetex XB-C18 column (100 × 3 mm, 100 Å, 2.6 μm particle size) held at 50 °C. The mobile phase was composed of 10 mM ammonium formate, pH 4.5 (solvent A) and acetonitrile (solvent B) the following LC method was used:

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>%A</th>
<th>%B</th>
<th>Flow rate (μL/min)</th>
</tr>
</thead>
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<tr>
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<td>2</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>98</td>
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</tr>
<tr>
<td>5.5</td>
<td>2</td>
<td>98</td>
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</tr>
<tr>
<td>8.5</td>
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<td>400</td>
</tr>
<tr>
<td>9.5</td>
<td>98</td>
<td>2</td>
<td>400</td>
</tr>
<tr>
<td>12.75</td>
<td>98</td>
<td>2</td>
<td>400</td>
</tr>
</tbody>
</table>

The mass spectrometer was operated in positive ion mode using the following parameters: Curtain gas: 20 L/min, Collision gas: medium, IonSpray voltage: 4500 V, Temperature: 250 °C, Ion source gas 1: 20 L/min, Ion source gas 2: 10 L/min. Declustering potential: 0, Entrance potential: 10, Collision cell exit potential: 10. Coumaroyl-CoA was detected in multiple reaction monitoring (MRM) mode by monitoring the following transition: 914.16 m/z → 407.16 m/z using a collision energy of 47.8 V. Data was imported into Skyline targeted mass spectrometry environment (v. 3.7.0 11317) and peaks were integrated using Skyline’s embedded integration function. Coumaroyl-CoA was quantified relative to a standard curve that was generated by calculating the linear regression of 3 individual injections of each concentration within the standard curve (R² = 0.9982).

Contributions


Declaration of competing interest

J.D.K. has financial interests in Amyris, Lygos, Demetrix, Napigen and Maple Bio.

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