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Production of curcuminoids from tyrosine by a metabolically engineered Escherichia coli using caffeic acid as an intermediate


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Abbreviations:

4CL, 4-coumaroyl-CoA ligase; ACC, acetyl-CoA carboxylase; C3H, 4-coumarate 3-hydroxylase; CCoAOMT, caffeoyl-CoA 3-O-methyltransferase; CURS, curcumin synthase; CUS, curcuminoid synthase; DCS, diketide-CoA synthase; TAL, tyrosine ammonia lyase
Abstract

Curcuminoids are phenylpropanoids with high pharmaceutical potential. Herein, we report an engineered artificial pathway in *Escherichia coli* to produce natural curcuminoids through caffeic acid. *Arabidopsis thaliana* 4-coumaroyl-CoA ligase (4CL1) and *Curcuma longa* diketide-CoA synthase (DCS) and curcumin synthase (CURS1) were used to produce curcuminoids and 70 mg/L of curcumin was obtained from ferulic acid. Bisdemethoxycurcumin and demethoxycurcumin were also produced, but in lower concentrations, by feeding *p*-coumaric acid or a mixture of *p*-coumaric acid and ferulic acid, respectively. Additionally, curcuminoids were produced from tyrosine through the caffeic acid pathway. To produce caffeic acid, tyrosine ammonia lyase (TAL) from *Rhodotorula glutinis* and 4-coumarate 3-hydroxylase (C3H) from *Saccharothrix espanaensis* were used. Caffeoyl-CoA 3-O-methyltransferase (CCoAOMT) from *Medicago sativa* was used to convert caffeoyl-CoA to feruloyl-CoA. Using caffeic acid, *p*-coumaric acid or tyrosine as a substrate, 3.9 mg/L, 0.3 mg/L and 0.2 mg/L of curcumin were produced, respectively. This is the first time DCS and CURS1 were used *in vivo* to produce curcuminoids and that curcumin was produced by feeding tyrosine. We have shown that curcumin can be produced using a pathway through caffeic acid. This alternative pathway represents a step forward in the heterologous production of curcumin using *E. coli*. 
1 Introduction

Curcuminoids are natural phenylpropanoids from the plant Curcuma longa Linn. Its rhizome contains a mixture of curcuminoids, with curcumin, demethoxycurcumin and bisdemethoxycurcumin present in higher amounts. These compounds present in turmeric have long been used in traditional Asian food and medicine. Their therapeutic properties include anticancer, anti-inflammatory, anti-oxidant, anti-Alzheimer’s, anti-HIV and anti-Parkinson [1-4]. Despite their numerous benefits to human health, curcuminoids have poor bioavailability and their natural abundance is low, thus making their heterologous biosynthetic production very interesting.

Recently, curcuminoids were found to be synthesized by type III polyketide synthases (PKSs) and additional enzymes from the phenylpropanoid pathway in plants [5]. Katsuyama et al. [6] were the first to produce curcuminoids using an artificial pathway in E. coli. They used phenylalanine ammonia lyase (PAL) from Rhodotorula rubra with tyrosine ammonia lyase (TAL) activity to convert the amino acids phenylalanine and tyrosine directly to cinnamic acid and p-coumaric acid. 4-coumarate-CoA ligase (4CL) from Lithospermum erythrorhizon was used to convert cinnamic acid and p-coumaric acid to cinnamoyl-CoA and p-coumaroyl-CoA, respectively, and then to curcuminoids by curcuminoid synthase (CUS) from Oryza sativa. Acetyl-CoA carboxylase (ACC) from Corynebacterium glutamicum was also overexpressed to increase the intracellular pool of malonyl-CoA. The supplementation of amino acids to the medium led to the production of bisdemethoxycurcumin and other two curcuminoids, cinnamoyl-p-coumaroylmethane and dicinnamoylmethane. The direct supplementation of carboxylic acids, as ferulic acid for instance, led to other curcuminoids including curcumin and demethoxycurcumin [6]. By adding two different unnatural carboxylic acids simultaneously (analsogs of p-coumaric acid), Katsuyama and coworkers also produced
unnatural curcuminoids [7]. Moreover, Wang et al. [8] produced the curcuminoid dicinnamoylmethane by using PALs from *Trifolium pratense*, 4CL1 from *Arabidopsis thaliana* and CUS from *O. sativa*. After CUS was discovered, Katsuyama et al. [9] reported that in the *C. longa* plant, the PKSs used to produce curcuminoids were diketide-CoA synthase (DCS) and curcumin synthase (CURS1). They also identified other CURS enzymes (CURS2 and CURS3) with different substrate specificities [10]. It is important to bear in mind that CUS catalyzes both steps that are catalyzed separately by DCS and CURS [9] (Fig. 1).

In this work, we describe curcuminoids production in *E. coli* using an artificial pathway (Fig. 1). We tested 4CL1 from *Arabidopsis thaliana* (*At*4CL1) and different PKSs for curcuminoids production (CUS, DCS and CURS1). Curcumin, demethoxycurcumin and bisdemethoxycurcumin were produced by adding ferulic acid and/or *p*-coumaric acid as precursors. To produce curcuminoids, including curcumin, from the amino acid tyrosine, caffeic acid had to be produced as an intermediate in the pathway. TAL from *Rhodotorula glutinis* and 4-coumarate 3-hydroxylase (C3H) from *S. espanaensis* were selected to produce caffeic acid based on the results obtained in our previous work (*manuscript submitted*). Caffeoyl-CoA was converted to feruloyl-CoA by CCoAOMT from *Medicago sativa*. This alternative pathway through caffeic acid allowed, for the first time, the production of curcumin, the most studied curcuminoid for therapeutic purposes and considered in many studies as the most potent and active [3-4], from the amino acid tyrosine, thus representing an advance in the heterologous production of curcumin by *E. coli*.

### 2 Materials and methods

#### 2.1 Bacterial strains, plasmids and chemicals
*E. coli* NZY5α competent cells (NZYTech, Lisbon, Portugal) were used for molecular cloning and vector propagation and *E. coli* K-12 MG1655(DE3) [11] was used as the host for the expression of genes under T7 promoter control. The characteristics of all the strains and plasmids used in this study are described in Table 1. TAL, C3H, DCS, CURS, CUS and CCoAOMT genes were codon-optimized for *E. coli*, synthesized and cloned in the plasmid vector pUC57 by GenScript (Piscataway, NJ, USA) or NZYTech (Lisbon, Portugal). The DNA sequences of the codon-optimized genes are provided in Supplementary Material (Table S1). pAC_At4CL1 was purchased from Addgene (Cambridge, MA, USA).

Restriction and ligation enzymes (NEB, Ipswich, MA, USA), KAPA HiFi DNA Polymerase enzyme (Kapa Biosystems, Wilmington, MA, USA), NucleoSpin® Plasmid Miniprep Kit (Macherey-Nagel, Düren, Germany) and DNA Clean and Concentrator and Gel DNA Recovery Kits (Zymo Research, Orange, CA, USA) were used according to the instructions provided by the manufacturers.

L-tyrosine, p-coumaric, caffeic acid, demethoxycurcumin and bisdemethoxycurcumin were purchased from Sigma-Aldrich (Steinheim, Germany), ferulic acid from Acros (Geel, Belgium), curcumin from Fisher Scientific (Loughborough, UK), isopropyl β-D-thiogalactopyranoside (IPTG) and Luria-Bertani (LB) medium from NZYTech (Lisbon, Portugal) and anhydrotetracycline (aTc) from Acros. Glucose (Acros), Na₂HPO₄ (Scharlau, Sentmenat, Spain), MgSO₄, KH₂PO₄ (Riel-deHaën, Seelze, Germany), NH₄Cl, NaCl, CaCO₃ (Panreac, Barcelona, Spain) and thiamine (Fisher Scientific, Loughborough, UK) were used to prepare the M9 modified salt medium. The following mineral traces and vitamins were supplemented to the M9 medium: FeCl₃, ZnCl₂, CoCl₂, CuCl₂, nicotinic acid (Riedel-deHaën), NaMoO₄, H₂BO₃, pyridoxine, biotin, folic acid (Merck), riboflavin and pantothenic acid (Sigma Aldrich). Ampicillin
(Applichem, Darmstadt, Germany), chloramphenicol, kanamycin (NZYtech) and spectinomycin (Panreac) were used when necessary.

2.2 Construction of plasmids

The genes encoding CUS, CURS, DCS, CCoAOMT, TAL and C3H were expressed in *E. coli* cells using the pETDuet-1, pCDFDuet-1, pRSFDuet-1 and pKVS45 vectors (Table 1) and were cloned using the appropriate restriction enzymes (Table S2).

All constructed plasmids herein described were verified by colony PCR or digestion and confirmed by sequencing (Macrogen, Amsterdam, The Netherlands).

2.3 Curcuminoids Production

*E. coli* cells for gene cloning, plasmid propagation, and inoculum preparation were grown in LB medium at 37 ºC and 200 rpm.

For the production of curcuminoids, the cultures were grown at 37 ºC in LB (50 mL) to an optical density at 600 nm of 0.3-0.4. IPTG and/or aTc were added (final concentration of 1 mM and 100 ng/mL, respectively) to induce protein expression. The culture was then incubated for 5 h at 26 ºC. Next, the cells were harvested by centrifugation, suspended, and incubated at 26 ºC for 63 h in modified M9 minimal salt medium (50 mL) containing (per liter): glucose (40 g), Na₂HPO₄ (6g), KH₂PO₄ (3g), NH₄Cl (1g), NaCl (0.5 g), CaCl₂ (17 mg), MgSO₄ (58 mg), thiamine (340 mg) and CaCO₃ (5 g) (to control the pH). Trace elements [FeCl₃ (54 mg), ZnCl₂ (4 mg), CoCl₂ (4 mg), NaMoO₄ (4 mg), CuCl₂ (2 mg) and H₂BO₃ (1 mg)] and vitamins [riboflavin (0.84 mg), folic acid (0.084 mg), nicotinic acid (12.2 mg), pyridoxine (2.8 mg), biotin (0.12 mg) and pantothenic acid (10.8 mg)] were also supplemented to the M9 medium.
Depending on the plasmid(s) present in the strain, ampicillin (100 µg/mL), spectinomycin (100 µg/mL), chloramphenicol (30 µg/mL) and/or kanamycin (50 µg/mL) were added. aTc and IPTG were added at the same time. Substrates were added at time 0 of induction in M9 medium (unless otherwise stated): tyrosine (3 mM), p-
coumaric acid (2 mM), caffeic acid (1 mM) and ferulic acid (2 mM). All the experiments were performed in triplicate unless otherwise specified.

2.4 Curcuminoids extraction

For posterior analysis, 2 mL of culture broth were taken at several points during the fermentation and adjusted to pH 3.0 with HCl (6 M). Then, the curcuminoids present in the samples were extracted with an equal volume of ethyl acetate. The extraction procedure was performed more than once for the cases in which the presence of curcuminoids inside the cells after the first extraction was still visible to the naked eye (yellow coloration). The extracts were concentrated by solvent evaporation in a fume hood, suspended in at least 200 µL of acetonitrile and then subjected to product analysis by high-performance liquid chromatography (HPLC).

2.5 HPLC analysis of the products

HPLC analysis was used to quantify p-coumaric acid, caffeic acid, ferulic acid, curcumin, demethoxycurcumin and bisdemethoxycurcumin using a system from Jasco (Easton, MD, USA) (PU-2080 Plus Pump unit, LG-2080-02 Ternary Gradient unit, a DG-2080-53 3-Line Degasser unit, a UV-2075 Plus Intelligent UV/VIS Detector unit and AS-2057 Plus Intelligent Sampler unit) and a Grace Alltech Platinum EPS C18
column (3µm, 150 mm × 4.6 mm) (Grace, Columbia, MD, USA). Mobile phases A and B were composed of water (0.1% trifluoroacetic acid) and acetonitrile, respectively. For the hydroxycinnamic acids quantification, the following gradient was used at a constant flow rate (1 mL/min): 10 - 20% acetonitrile (mobile phase B) for 16 min. Quantification was based on the peak areas obtained at 310 nm for p-coumaric acid, caffeic acid and ferulic acid. The retention times of p-coumaric acid, caffeic acid and ferulic acid were 8.0, 11.8 and 13.8 min, respectively. For the curcuminoids quantification, a gradient of 40 - 43% acetonitrile (mobile phase B) for 15 min and 43% acetonitrile for an additional 5 min was used. The curcuminoids were detected at 425 nm and the retention times of bisdemethoxycurcumin, demethoxycurcumin and curcumin were 12.4, 13.5 and 14.5 min, respectively.

2.6 Protein Analysis

E. coli K-12 MG1655(DE3) cells harbouring pRSFDuet_CUS, pRSFDuet_CURS, pRSFDuet_DCS and pRSFDuet_CCoAOMT were grown in LB at 37 ºC to an optical density at 600 nm of 0.6. IPTG was added (at a final concentration of 1 mM) to induce protein expression, and the culture was incubated for 5 h. Samples (10 mL culture medium) were taken at time 0 and 5 h of induction. Samples were centrifuged and the cells were suspended in phosphate-buffered saline (PBS: 137 mM NaCl, 2.7 mM KCl, 10 mM Na₂PO₄, 1.8 mM KH₂PO₄, pH 7.4) and disrupted by sonication on ice for 3 min. After centrifugation, the protein concentration from the resulting supernatant was determined using Protein Assay Dye Reagent Concentrate (BioRad, Hercules, CA, USA) and bovine gamma globulin (BSA) (NEB) as a standard. The expression levels of the enzymes were examined using sodium dodecyl sulfate polyacrylamide gel electrophoretic (SDS –PAGE) analysis. Fifteen to 20 µg of total protein were loaded in
4-20 % Mini-PROTEAN® TGX™ Precast Gels (BioRad). The protein marker used was Precision Plus Protein™ Unstained (BioRad) and/or ColorPlus™ Prestained Protein Ladder Broad Range (NEB). For gel staining, Bio-Safe Coomassie Stain (BioRad) was used.

3 Results

3.1 The 4-coumarate-CoA ligase (4CL)

4CL enzymes convert the hydroxycinnamic acids (p-coumaric acid, caffeic acid and ferulic acid) to their corresponding CoA esters (p-coumaroyl-CoA, caffeoyl-CoA and feruloyl-CoA) (Fig. 1) with different substrate preferences and specificities. We studied three different 4CL enzymes (LeAt4CL1, At4CL2 and At4CL1) and only At4CL1 was found to be functionally expressed. Recently, this enzyme was successfully used in the production of curcuminois [8] and in stilbene and flavonoid biosynthesis [12, 13]. In the current work, this enzyme was tested in vivo with CUS and CURS1/DCS. Since the results obtained regarding the production of curcuminois were positive, all the further optimization tests were performed using this 4CL enzyme.

3.2 Production of curcuminois using CUS from O. sativa

Codon-optimized CUS was cloned in pRSFDuet-1 and its expression was confirmed on a protein gel (44.3 kDa) (Fig. S1). After that, CUS was tested in E. coli with At4CL1 (pRSFDuet_CUS + pAC_At4CL1) (Fig. 2). These enzymes produced bisdemethoxycurcumin and curcumin when p-coumaric acid and ferulic acid,
respectively, were added to the culture medium. Curcumin was produced in higher amount (6.7 µM) than bisdemethoxycurcumin (0.9 µM).

Additionally, we found that the production of curcuminoids at 24 h is lower compared to 63 h which is in agreement with the results reported by Katsuyama et al. [6]. This difference is significant (4.5 times lower) when curcumin is produced compared to bisdemethoxycurcumin production. Also, a yellow color of the culture medium, due to the increase of curcuminoids inside the cells, could only be observed after 24 h. The production of curcuminoids, even at low concentrations (0.9 µM) could be easily detected after 63 h (Fig. S2, A and B) by the observation of some cells that adhered to the walls of the shake flasks.

To improve curcuminoids production, p-coumaric acid and ferulic acid were supplemented to the culture medium in two steps: 1 mM at time 0 of induction and 1 mM after 24 h of induction. However, the production decreased up to around 8.6 times. Bisdemethoxycurcumin was also produced from tyrosine using TAL from R. glutinis (cloned in pCDFDuet_TAL), At4CL1 and CUS. The production was very similar to that obtained in the experiment in which p-coumaric acid was added in two steps, which probably means that the production/concentration of p-coumaric acid in the first 24 h affects the production of bisdemethoxycurcumin. The production of p-coumaric acid at 63 h was around 1500 µM, thus suggesting that the TAL enzyme was highly functional.

### 3.3 Production of curcuminoids using DCS and CURS1 from C. longa

Codon-optimized DCS and CURS1 were cloned in pRSFDuet-1 and their protein expression was also confirmed on a protein gel (Fig. S1). The protein expression of DCS and CURS (42.9 kDa) was very high; hence in vivo production was further tested.
Fig. 3A illustrates the curcumin production from ferulic acid using pAC_At4CL1, pCDFDuet_DCS and pRSFDuet_CURS1. The production with these enzymes was very high, 187.9 µM (70 mg/L) after 63 h. Besides, the culture medium showed a dark orange color (Fig. S2D), thus suggesting the production of curcuminoids.

The addition of substrate (ferulic acid) was also tested at three different time points, namely 1 mM at time zero of induction in M9 medium, 0.5 mM at 5 h and an additional 0.5 mM 24 h after induction. As previously observed (Fig. 3A), the curcuminoids production was also significantly lower (5.5 times) with multiple additions compared to adding all the ferulic acid at time zero of induction.

To understand if the amount of cells (OD$_{600}$) at the time of induction in LB influenced the production of curcuminoids, we induced the cultures at different OD$_{600}$ values (Fig. 3B). We found that, although the cells should be induced early, induction should not be too early since it can impose a metabolic burden on the host strain associated with protein overexpression. The addition of IPTG at an OD$_{600}$ of 0.4 yielded the highest production titer (187.9 µM), thus suggesting that induction should be performed at an OD$_{600}$ of 0.3-0.4. Moreover, we tested the production by inducing the cells in LB and then in M9 at 37 ºC instead of 26 ºC. As expected the production of curcumin at 37 ºC was residual. Low temperatures, around 26-30 ºC, should be used for optimal enzyme synthesis and curcuminoids production.

Additionally, the effect of adding p-coumaric acid as a substrate, or a mixture of p-coumaric acid and ferulic acid in the production of other curcuminoids was also evaluated (Fig. 3C). The amount of bisdemethoxycurcumin produced was very low (5.0 µM) compared to curcumin (187.9 µM), albeit 5 times higher than that obtained when CUS was used instead of DCS and CURS1. The addition of both substrates enabled the
production of bisdemethoxycurcumin, demethoxycurcumin and curcumin. Curcumin
was produced at the highest concentration (0.6 µM), followed by demethoxycurcumin,
due to the preference of feruloy-CoA as a substrate, compared to \( p \)-coumaroyl-CoA.

Bisdemethoxycurcumin could also be produced from tyrosine, although in very small
amounts (Fig. 3D), i.e. almost 10 times lower than when \( p \)-coumaric acid is added. To
improve the curcuminoids production we cloned \( At4CL1 \) in \( pCDFDuet-1 \) with DCS,
however the curcumin production was extremely low (~ 0.1 µM) compared to that
obtained when \( At4CL1 \) was in \( pAC \) plasmid (187.9 µM).

### 3.4 Production of curcuminoids using caffeic acid as a precursor or intermediate

CCoAOMT (~27.3 kDa) was successfully expressed in \( E. coli \) (Fig. S3) and was used to
produce curcumin from caffeic acid. \( At4CL1 \) showed some specificity for caffeic acid
and CCoAOMT was found to be functional since curcumin was produced in vivo using
these enzymes (Fig. 4A). However, the curcumin concentration obtained was low (0.1 –
3.9 µM) as compared with the production from ferulic acid (187.9 µM). This lower
production is probably due to the \( At4CL1 \) specificity. The enzyme shows a much higher
preference for ferulic acid than for \( p \)-coumaric acid and caffeic acid. However, \( At4CL1 \)
seems to have a higher preference for caffeic acid than for \( p \)-coumaric acid since the
production of curcumin from caffeic acid and bisdemethoxycurcumin from \( p \)-coumaric
acid (Fig. 3C) was very similar although more steps are required to obtain curcumin.

We tested different approaches to clone CCoAOMT. CCoAOMT cloned in
\( pRSFDuet\_CURS1 \) leads to a significant production of curcuminoids, while if cloned in
\( pCDFDuet\_DCS \) the production is residual. Consequently, the first approach was
chosen to attempt the production of curcuminoids from tyrosine.
Curcuminoids production, including curcumin, was obtained from $p$-coumaric acid and tyrosine by using caffeic acid as an intermediate (Fig. 4B and C). When $p$-coumaric is used as a precursor, the production of curcuminoids is higher than when using tyrosine. Indeed, this was expected since, as the number of intermediates increases, the production of curcuminoids decreases, due to the loss of product in each step of the pathway. When $p$-coumaric acid is used as a substrate, bisdemethoxycurcumin is the curcuminoid produced in higher concentrations (~0.5 µM), followed by demethoxycurcumin. This occurs probably because, due to the high concentration of $p$-coumaric acid added, $p$-coumaroyl-CoA is present in a higher concentration than feruloyl-CoA, thus being more available to produce a higher concentration of bisdemethoxycurcumin and demethoxycurcumin. Also, pKVS45_C3H enabled a higher concentration of caffeic acid than pETDuet_C3H (Fig. 4C), as we have observed previously (manuscript submitted). Consequently, a higher caffeic acid concentration (299.5 µM) allowed the production of more curcumin (0.3 µM). When tyrosine is used as substrate, the caffeic acid concentration obtained is lower (79.9 - 174.4 µM), and the $p$-coumaric acid concentration produced is also lower (354.6 – 568.0 µM) than that maintained when it is added as a precursor (1392.6 – 1571.3 µM). Although $p$-coumaric is present in a higher concentration than caffeic acid (Fig.4C, (5) and (6)), $At4CL1$ seems to prefer caffeic acid over $p$-coumaric acid and consequently, curcumin (0.1 – 0.2 µM) is produced in higher amounts than bisdemethoxycurcumin (0.03 – 0.07 µM). The concentration of the asymmetric curcuminoid (demethoxycurcumin) is higher than the concentration obtained of the symmetric curcuminoids (curcumin and bisdemethoxycurcumin). The system using TAL and C3H in the same plasmid (pETDuet_TAL_C3H) works better than cloning TAL in pCDFDuet_DCS. In the latter case, low expression levels of TAL seems to be the cause, as was found for CCoAOMT.
(Fig. 4A), since the $p$-coumaric acid production was low (354.6 µM) and consequently the caffeic acid production was also low (79.9 µM), thus leading to a lower production of curcuminoids.

4 Discussion

Since there is an increasing interest in curcumin and other curcuminoids due to their several recognized beneficial effects, synthetic biology and metabolic engineering constitute good approaches to improve their availability. The discovery of CUS from *O. sativa* allowed the production of curcuminoids in *E. coli* [6, 7] and *in vitro* [14], which represented an important step forward in the production of curcuminoids using the above mentioned strategies. CUS has the advantage of catalyzing the three steps that are catalyzed by different PKSs (CURS and DCS) in *C. longa*: (a) condensation of malonyl-CoA with feruloyl-CoA (or other CoA ester) to produce diketide-CoA; (b) hydrolysis of diketide-CoA to its corresponding $\beta$-keto acid; and (c) decarboxylative condensation of the $\beta$-keto acid to the second molecule of feruloyl-CoA (Fig. 1). This enzyme would make the production of curcuminoids from tyrosine simpler by decreasing the number of enzymes needed for the pathway to function. In this study, we used CUS to produce the three main curcuminoids in *C. longa*: bisdemethoxycurcumin, demethoxycurcumin and curcumin. However, the amount of curcuminoids produced with CUS was lower than the expected. The low titers (0.9 µM of bisdemethoxycurcumin and 6.7 µM of curcumin) may be due to use of plant enzymes in the pathway, which usually are poorly stable in prokaryotes even with codon-optimization owing to the lack of specific protein folding chaperones and post-translational modifications. Ferulic acid and/or feruloyl-CoA seem to be the preferred substrates since curcumin was produced in higher amount than bisdemethoxycurcumin.
However, \textit{At}4CL1 was reported to prefer \textit{p}-coumaric acid to ferulic acid \cite{15} and Katsuyama et al. \cite{14} also concluded by \textit{in vitro} experiments that CUS prefers \textit{p}-coumaroyl-CoA as a substrate. Therefore, the reason behind the higher curcumin production in this study is not clear. However, \textit{in vivo} experiments by the same authors \cite{6} revealed that the CUS enzyme together with \textit{Le}4CL produces very similar amounts of bisdemethoxycurcumin and curcumin from \textit{p}-coumaric acid and ferulic acid, respectively, although the curcumin concentration obtained was slightly higher. It cannot be concluded if the higher concentration of curcumin obtained \textit{in vivo} was due to \textit{Le}4CL substrate specificity, since it is unknown.

DCS and CURS1 were also chosen to test the curcuminoids production due to the promising results previously reported \textit{in vitro} \cite{9,10,16}. Although these two genes were successfully expressed in \textit{E. coli} and the enzymes were used to produce several curcuminoids, including curcumin, DCS and CURS1 were never tested \textit{in vivo}. CURS1 was named curcumin synthase due to its pronounced preference for feruloyl-CoA \cite{9}. Moreover, other CURS were identified. CURS2 was also reported to prefer feruloyl-CoA and CURS3 favored both feruloy-CoA and \textit{p}-coumaroyl-CoA \cite{10}. Since curcumin has been reported to possess, in some systems, a higher therapeutic value than the other curcuminoids \cite{17}, CURS1 was chosen as it has the highest turnover rate towards feruloyl-CoA, as well as the highest difference between the catalytic efficiency towards feruloyl-CoA and \textit{p}-coumaroyl-CoA \cite{10}. The production of curcumin using CURS1 and DCS was surprisingly higher than we expected (187.9 $\mu$M), especially taking into account the results obtained with CUS. This is the first report that demonstrates that these two enzymes can be used efficiently to produce curcuminoids in \textit{E. coli} and provide high production titers. A higher concentration (113 mg/L) was reported using \textit{Le}4CL, CUS and ACC \cite{6}. It is important to note that ACC can be very
important to obtain high curcuminoids titers, in particular if there is a limitation of malonyl-CoA in the cells. However, comparing the results from Katsuyama et al. [6] and Wang et al. [8] we can conclude that a high production of curcuminoids can also be obtained without ACC overexpression. Katsuyama et al. [6] when using *R. rubra* PAL, *Le*4CL, CUS and ACC, and adding phenylalanine or cinnamic acid were able to obtain around 107 mg/L or 84 mg/L of dicinnamoylmethane, respectively; while Wang et al. [8] by using *T. pratense* PAL, *At*4CL1 and CUS, and adding phenylalanine obtained 360 mg/L of dicinnamoylmethane – i.e. a dicinnamoylmethane concentration 3.4 times higher without the need of using overexpressed ACC to increase the malonyl-CoA pool in *E. coli*. Even though Wang et al. [8] obtained high production of dicinnamoylmethane and we were able to achieve a high production of curcumin, the ACC requirements should be further evaluated to confirm if malonyl-CoA is limiting the production of curcuminoids.

To improve curcuminoids production, the substrates were supplemented to the culture medium in two steps. This stepwise approach was tested due to the possible toxicity of *p*-coumaric and ferulic acids to the cells [12, 18-22], and because we found that this strategy improved the production of caffeic acid in our previous work (*manuscript submitted*). However, in the current study the two-step feeding was shown to be counterproductive, i.e. the production decreased which means that the slow process of curcuminoids production requires all the substrate available at the beginning of the fermentation to achieve a high production.

The previous report on the heterologous production of curcumin involves the direct supplementation of ferulic acid in the culture medium [6]. To our knowledge, this is the first report on the production of curcumin from tyrosine through the production of caffeic acid as an intermediate. CCoAOMT from *M. sativa* was used to catalyze the
methylation of caffeoyl-CoA, its preferred substrate, to feruloyl-CoA and it was chosen since it has already been expressed in E. coli [23]. After At4CL1 converts caffeic acid to caffeoyl-CoA, CCoAOMT converts caffeoyl-CoA to feruloyl-CoA which DCS and CURS1 can convert to curcumin. To date, the levels of production are not very high; however these can be improved by balancing different expression levels. Imbalances can lead to over- or underproduction of enzymes and accumulation of intermediate metabolites which may result in suboptimal titers. CURS1 has a higher preference for feruloyl-CoA than for p-coumaroyl-CoA. However, the DCS preference for p-coumaric acid or ferulic acid is unknown, although it is established that its affinity for malonyl-CoA is high [9]. At4CL1 was reported to have a high affinity for p-coumaric acid, followed by caffeic acid and a very low specificity for ferulic acid [15], which seems to be contradicted by our results. All these issues make it difficult to control the curcuminoids production ratios, and more information about the catalytic properties of all the enzymes involved in the curcuminoids biosynthetic pathway is required. Although up to now the production of curcuminoids from tyrosine is low (up to 0.6 µM) and the curcuminoids ratio difficult to control, this alternative pathway successfully led to the production of curcumin from tyrosine. Curcumin, the most studied curcuminoid for therapeutic purposes and in many studies considered as the most potent and active [3-4], was only shown to be produced in E. coli using ferulic acid. This represents a disadvantage when the production cost of curcumin is relevant, but also for the cases in which curcumin is used as a drug that needs to be produced and delivered in situ. By producing curcumin using tyrosine (endogenous amino acid) and using (in the future) a tyrosine overproducing strain, the need to add expensive precursors disappears and the production process is also simplified. Although it is clear that the pathway herein described, depending on the application, has to be further refined and optimized this is
the first step towards the production of curcumin from an amino acid in *E. coli* and it is also the first time that caffeic acid is used as an intermediate to produce curcuminoids. Therefore, this alternative pathway represents a significant progress in the heterologous production of curcumin using *E. coli*.

**Acknowledgements**

This work was supported by FEDER funds through the COMPETE and ON2 program and through National funds of FCT in the scope of the project FCOMP-01-0124-FEDER-027462, PEst-OE/EBB/LA0023/2013, NORTE-07-0124-FEDER-000028 and NORTE-07-0124-FEDER-000027. Financial support for this work was provided by FCT grant SFRH / BD / 51187 / 2010 and SYNBIOBACTHER project (PTDC/EBB-BIO/102863/2008).

The authors declare no commercial or financial conflict of interest.

**5 References**

## Table 1. Bacterial strains and plasmids used in this study

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<tr>
<td><strong>E. coli K-12 MG1655 DE3</strong></td>
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<td>ColE1(pBR322) <em>ori, lacI</em>, double T7lac, Amp&lt;sup&gt;R&lt;/sup&gt;</td>
<td>Novagen</td>
</tr>
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<td>this study</td>
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<td>Description</td>
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**Figure Legends:**

**Figure 1.** Proposed curcuminoids biosynthetic pathway in *E. coli* and the reactions catalyzed by the enzymes in this study. TAL: tyrosine ammonia lyase; C3H: 4-coumarate 3-hydroxylase; 4CL: 4-coumarate-CoA ligase; CCoAOMT: caffeoyl-CoA 3-O-methyltransferase; DCS: diketide-CoA synthase; CURS1: curcumin synthase; CUS: curcuminoid synthase.

**Figure 2.** Curcuminoids production from *p*-coumaric acid and ferulic acid using 4-coumarate-CoA ligase (4CL1) from *Arabidopsis thaliana* and curcuminoid synthase (CUS) from *Oryza sativa*. Bisdemethoxycurcumin was also produced from tyrosine using tyrosine ammonia lyase (TAL) from *Rhodotorula glutinis*. Error bars are standard deviations from triplicate experiments.

**Figure 3.** Curcuminoids production using 4-coumarate-CoA ligase (4CL1) from *Arabidopsis thaliana* and diketide-CoA synthase (DCS) and curcumin synthase 1 (CURS1) from *Curcuma longa*. Curcumin production from ferulic acid (A). Effect of IPTG induction at different OD$_{600}$ values and effect of induction temperature on the production titers of curcumin using ferulic acid as substrate (B). Curcuminoids production from *p*-coumaric acid and a mixture of *p*-coumaric acid and ferulic acid (C). Bisdemethoxycurcumin production from tyrosine using tyrosine ammonia lyase (TAL) from *Rhodotorula glutinis* and curcumin production from ferulic acid using a different plasmid configuration (D). Error bars are standard deviations from triplicate experiments.

**Figure 4.** Curcumin production from caffeic acid using caffeoyl-CoA 3-O-methyltransferase (CCoAOMT) from *Medicago sativa*, 4-coumarate-CoA ligase (4CL1) from *Arabidopsis thaliana* and diketide-CoA synthase (DCS) and curcumin synthase 1 (CURS1) from *Curcuma longa* (A). Curcuminoid production from *p*-coumaric acid and tyrosine using caffeic acid as an intermediate and using tyrosine ammonia lyase (TAL) from *Rhodotorula glutinis*, 4-coumarate 3-hydroxylase (C3H) from *Saccharothrix espanaensis*, CCoAOMT 4CL1, DCS and CURS1. In (B) bisdemethoxycurcumin, demethoxycurcumin and curcumin production are shown while in (C) *p*-coumaric acid and caffeic acid are reported. Error bars are standard deviations from triplicate experiments.
Fig1
(1) Bisdemethoxycurcumin; 2 mM \( p \)-coumaric acid
(2) Bisdemethoxycurcumin; 1 mM \( p \)-coumaric acid + 1 mM \( p \)-coumaric acid at 24 h
(3) Bisdemethoxycurcumin; 3 mM tyrosine
(4) Curcumin; 2 mM ferulic acid
(5) Curcumin; 1 mM ferulic acid + 1 mM ferulic acid at 24 h
Fig3

(1) 2 mM ferulic acid
(2) 1 mM ferulic acid + 0.5 mM at time 5 h + 0.5 mM at time 24 h

Optical density at induction time and temperature during induction

(1) 2 mM p-coumaric acid; pAC_At4CL1 + pCDFDuet_DCS + pRSFDuet_CURS1
(2) 1 mM p-coumaric acid + 1 mM ferulic acid; pAC_At4CL1 + pCDFDuet_DCS + pRSFDuet_CURS1
(3) 3 mM tyrosine; pETDuet_TAL + pAC_At4CL1 + pCDFDuet_DCS + pRSFDuet_CURS1
(4) 2 mM ferulic acid; pCDFDuet_DCS_At4CL1 + pRSFDuet_CURS1
A

(1) pAC_A4CL1 + pCDFDuet_DCS + pRSFDuet_CURS1_CCoAOMT
(2) pAC_A4CL1 + pCDFDuet_DCS_CCoAOMT + pRSFDuet_CURS1

B

- Bisdemethoxycurcumin
- Demethoxycurcumin
- Curcumin

C

- Caffeic acid
- p-coumaric acid

(3) p-coumaric acid; pKVS45_C3H + pRSFDuet_CURS1_CCoAOMT + pCDFDuet_DCS + pAC_A4CL1
(4) p-coumaric acid; pETDuet_C3H + pRSFDuet_CURS1_CCoAOMT + pCDFDuet_DCS + pAC_A4CL1
(5) tyrosine; pETDuet_TAL_C3H + pRSFDuet_CURS1_CCoAOMT + pCDFDuet_DCS + pAC_A4CL1
(6) tyrosine; pETDuet_C3H + pRSFDuet_CURS1_CCoAOMT + pCDFDuet_DCS_TAL + pAC_A4CL1

Fig4
Supplementary Material

Production of curcuminoids from tyrosine by a metabolically engineered *Escherichia coli* using caffeic acid as an intermediate

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\(^2\)Department of Chemical Engineering, Synthetic Biology Engineering Research Center (SynBERC) Massachusetts Institute of Technology, Cambridge, MA 02139, USA

\(^3\)MIT-Portugal Program, Cambridge, MA and Lisbon, Portugal
<table>
<thead>
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<th>Gene</th>
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<td><strong>C3H</strong> <em>(Saccharothrix espanaensis)</em></td>
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CCoAOMT
*(Medicago sativa)*

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GTTACGCTGACGAATGGAAGTTACCGGCACCACGCACTTCCGCGGTGTTCAGGCGCAGAAGTCGGCGAAGTGCTGAACTGGCGTGATGTCT
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GGTATTCGTGTGCAGACCTCGAAGACCTATCAAGGCAAATGGTCAAGCGGCCGCACTGAAAGGCTTTGCGGAACAGTGTATGTCGGAA
TATGACCGCTGGTAGTCCGGACACCCCGCACTTGGATTACATCGTCTGATTTAATAGTA

CUS
*(Oryza sativa)*

ATGGCCTCCGACCACGACGATGGGTTCCGCTCTGTAATCCCGCTGGTGAATGCGCCGTAGTCAACGCGCCGATGGCCTGGCAGCAGTC
CTACGCGCATGGCAACACGGCAATTTGGAAGGAAAATCCGGTCGCTGGGCAATGGCCGGAACTCGTTGAAAGCTGGCAAGCCGCTGGT
CCTGCTGGACATTGCCGCGGATGCCGTTCCGGAACTGGCA

DCS
*(Curcuma longa)*

ATGGAAAGCTAACCCGCCTTTGGATGAAATGCGCCGCTATCCCGCTGGTGAATGCGCCGTAGTCAACGCGCCGATGGCCTGGCAGCAGTC
CTACGCGCATGGCAACACGGCAATTTGGAAGGAAAATCCGGTCGCTGGGCAATGGCCGGAACTCGTTGAAAGCTGGCAAGCCGCTGGT
CCTGCTGGACATTGCCGCGGATGCCGTTCCGGAACTGGCA

GCTGGATGAGCGGTGCTACGGTTATCTTTGCGCTGGATGAACTGCGTCGCCAACGCAAAGAAGCCGCAGCTGCGGGTGAATGGCCGGAACTG
GGTGTTATGATGGCCTTTGGTCCGGGTATGACGGTTGATGCGATGCTGCTGCACGCCACGAGCCATGTGAACTAA
| TCGTCGCAAAATCTGACATCACCCACCTGGTTTTCTGCTCTGCTTCTGGTATCGACATGCCGGGTTCTGACCTGCAGCTGCTGAAACTGC | **CURS1**  
\textit{(Curcuma longa)} | ATGGCTAACCTGCACGCTCTGCGTCGTGAACAGCGTGCTCAGGGTCCGGCT ACCATCATGGCTATCGGTACCGCTACCCCGCCGAACCTGTACGAAACATCTCACCTCTCCGGGACTTCTACTTCCGTGTTACCAACTCTGACGACAAACAGGAACTGAAAAAAAAATTCCGTCGTATGTGCGAAAAAACCATGGTTAAAAAACGTTACCTGCACCTGACCGAAGAAATCCTGAAAGAACGTCCGAAACTGTGCTCTTACAAAGAAGCTTCTTTCGACGACCGTCAGGACATCGTTGTTGAAGAAATCCCGCGTCTGGCTAAAGAAGCTGCTGAAAAAGCTATCAAAGAATGGGGTCGTCCGAAATCTGAAATCACCCACCTGGTTTTCTGCTCTATCTCTGGTATCGACATGCCGGGTGCTGACTACCGTCTGGCTACCTGCTGGGTCTGCCGCTGACCGTTAACCGTCTGATGATCTACTCTCAGGCTTGCCACATGGGTGCTGCTATGCTGCGTATCGCTAAAACACCTGGCTGAAAACAACCGTGGTGCTCGTGTTCTGGTTGTTGCTTGCGAAATCACCGTTCTGTCTTTCCGTGGTCCGAACGAAGGTAATTCGAAGCTCTGGCTGGTCAGGCTGGTTTCGGTGACGGTGCTGGTGCTGTGTTGTTGGTGCTGACCCGCTGGAAGGTATCGAAAAACCGATCTACGAAATCGCTGCTGCTATGCAGGAAACCGTTGCTGAATCTCAGGGTGCTGTTGGTGGTCACCTGCGTGCTTTCGGTTGGACCTTCTACTTCCTGAACCAGCTGCCGGCTATCATCGCTGACAACCTGGTCCGTTCTCTGGAACGTGCTCTGGCTCCGCTGGGTGTTCGTGAATGGAACGACGTTTTCTGGGTTGCTCACCCGGGTAACTGGGCTATCATCGACGCTATCGAAGCTAAACTGCAGCTGTCTCCGGACAAACTGTCTACCGCTCGTCACGTTTTCACCGAATACGGTAACATGCAGTCGGCGACCGTCTACTTCGTGATGGACGAACTGCGTAAACGTTCTGCTGTTGAAGGTCGTTCTACCACCGGCGACGGTCTGCAGTGGGGTGTTCTGCTGGGTTTCGGTCCAGGTCTGTCTATCGAACCGTTGTTCTGCGTTCTATGCCGCTGTAA |
Table S2. Set of primers for PCR amplification (forward (FW) and reverse (REV) primers)

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[a] Start and stop codons in **bold**; restriction sites in *italic*; His6-Tag underlined; In order for the sequence to remain in frame one or two bases were occasionally added between the restriction site and the gene start codon.

Figure S1. Protein gel showing DCS, CURS1 and CUS expression in cell-free extracts at time zero of induction and after 5 hours of induction. DCS and CURS1 have 42.90 kDa and
CUS has 44.33 kDa. DCS: diketide-CoA synthase; CURS1: curcumin synthase; CUS: curcuminoid synthase; M: Marker.

Figure S2. Curcuminoid production can be observed by the yellow/orange color of the cells. Bisdemethoxycurcumin (A, C) and curcumin (B, D) were produced using p-coumaric and ferulic acid as substrates, respectively. Two different combinations of enzymes were tested: CUS (A, B) and CURS1 and DCS (C, D). When curcuminoids are not produced the culture medium remains white (E). CUS: curcuminoid synthase; CURS1: curcumin synthase 1; DCS: diketide-CoA synthase.
Figure S3. Protein gel showing caffeoyl-CoA 3-O-methyltransferase (CCoAOMT) enzyme present in pRSFDuet-1 in cell-free extract. CCoAOMT is expected around 27.28 kDa.