**Co-expression of onion *chalcone isomerase* in *Del/Ros1*-expressing tomato enhances anthocyanin and flavonol production**

Wansang Lim1 and Jiarui Li2

1HFRR, Throckmorton Kansas State University Manhattan, KS 66506 U.S.A

Phone: 607-227-3265, E-mail:wl73@cornell.edu

2Department of Plant Pathology, Throckmorton Kansas State University Manhattan, KS 66506 U.S.A

Abstract

Anthocyanins are colorful pigments known for contributing antioxidant effects to the human diet which provide health benefits that protect against several forms of cancer and vascular disease. Unfortunately, tomatoes found in nature have very low anthocyanin content. Anthocyanin rich, purple tomatoes by the ectopic co-expression of two transcription factors *Delila* (*Del*) and *Rosea1* (*Ros1*) from the snapdragon *Antirrhinum majus* have been generated. However, the *Del/Ros1* (*DR*)-expressing tomatoes cannot sufficiently upregulate all necessary key endogenous genes, particularly chalcone isomerase (*CHI*), for full utilization of the anthocyanin production pathway. In this study, *CHI* from onion *Allium cepa* was introduced into *DR*-expressing tomatoes for a further increase of anthocyanin levels in both the peel and the flesh of tomatoes*.* We achieved up to 400-fold and 260-fold increases in the levels of anthocyanins in tomato peel and flesh, respectively, in *CHI/DR* transgenics compared with 100-fold and 120-fold increases in tomato peel and flesh in the *DR* only expressing lines. Furthermore, *CHI/DR*-expressing tomatoes increased up to 200-fold more total flavonol content compared with the wild-type tomatoes. In summary, stacking *CHI* with *DR* could significantly increase the levels of anthocyanins and flavonols in tomato fruit.

Introduction

Anthocyanins are a subgroup of dietary phenolics that are responsible for the purple color of various fruits and vegetables and have been associated with potentially health-beneficial effects in various diseases, such as cardiovascular disease ([Lee et al. 2007](#_ENREF_12); [Wallace 2011](#_ENREF_28)), diabetes ([Ghosh and Konishi 2007](#_ENREF_5)), and cancer ([Seeram et al. 2006](#_ENREF_24); [Shih et al. 2005](#_ENREF_25)). In addition, anthocyanins have the capacity to modulate cognitive and motor functions, enhance memory, hinder obesity, and prevent age-related decline ([Cho et al. 2003](#_ENREF_3)). Another bioactive flavonoid, rutin is the most abundant flavonol in tomatoes ([Colliver et al. 2002](#_ENREF_4)), albeit present in very small amount. Rutin also exhibits a range of pharmacological effects such as anti-oxidation, anti-inflammation, and anti-hypertension as well as vasoconstrictive, spasmolytic, and positive inotropic effects ([Kuntic et al. 2011](#_ENREF_9); [La Case et al. 2000](#_ENREF_10); [Landberg et al. 2011](#_ENREF_11)). Although tomatoes are one of the most popular fruits used in many diets, they have a very low overall anthocyanin and flavonol content and, therefore, increasing the total anthocyanin and/or flavonol content of tomatoes has been an important objective to researchers because these beneficial effects depend on relatively high levels of dietary anthocyanins and flavonols ([Butelli et al. 2008](#_ENREF_2); [Muir et al. 2001](#_ENREF_18)).

Although tomato is a popular fruit used in many diets, it has a very low overall flavanoid and anthocyanin content. Flavonoids accumulate in tomatoes in a tissue-specific way. Flavonols, including rutin, are present mostly in peel of the tomato, while only traceable amounts are present in the flesh. Similarly, tomato peel has a very small amount of anthocyanin and the flesh has almost no anthocyanin. This is a stark contrast to other fruits of the *Solanaceae* family such as eggplant and pepper ([Zuluaga et al. 2008](#_ENREF_30)). This is due to the fact that the flavonoid pathway is not active in the fruit flesh due to expression of specific flavonoid biosynthetic genes that downregulate the pathway in the tissue ([Bovy et al. 2002](#_ENREF_1); [Colliver et al. 2002](#_ENREF_4); [Verhoeyen et al. 2002](#_ENREF_27)).

The red color that tomatoes and some peppers, exhibit at the ripening stage is due to the carotenoid lycopene rather than anthocyanin. Most health beneficial effect of tomato is due to lycopene. Because tomatoes are quite popular and they contain lycopene, they are an ideal crop to increase anthocyanin content without the expense of lycopene so that they can provide health benefit to consumers with both lycopene and flavonoid.

Heterologous overexpression of either the structural or regulatory genes in the flavonoid pathway has been used to increase flavonoid levels or modify the flavonoid profile in tomatoes ([Gonzali et al. 2009](#_ENREF_6)). For example, the concurrent overexpression of both regulatory snapdragon genes *Delila* (*Del*) and *Rosea1* (*Ros1*) in tomatoes results in a marked increase in anthocyanin content (Butelli et al. 2008). This can be observed visually as the fruit develops and ripens into a purple color. Moreover, an overall increase in flavonol levels in tomato fruits has been achieved by simultaneous overexpression of the maize transcription factors *Lc* and *C1* ([Bovy et al. 2002](#_ENREF_1)). The Arabidopsis *MYB75*/*PAP1* transcription factor is also effective in specific local cells in the epidermal or cortical region or in proximity to a vascular bundler but is not quite as effective as in the fruit ([Zuluaga et al. 2008](#_ENREF_30)). Luo et al ([Luo et al. 2008](#_ENREF_17)) reported that *AtMYB12* increases polyphenol content by as much as 10% in the dry weight of tomato fruits. Each of these regulatory genes has a unique effect on the flavonoid profile of the fruit they are introduced into.

As an alternative approach, the concurrent overexpression of structural genes *CHI* (chalcone isomerase), *CHS* (chalcone synthase), *F3H* (flavanone-3-hyudroxylase) and *FLS* (flavonol synthase, Fig 1) increases levels of flavonols in tomato flesh, demonstrating that structural genes also play important roles in regulation of flavonoid synthesis pathway ([Verhoeyen et al. 2002](#_ENREF_27)). In addition, it is possible to achieve an increase of up to 78-fold flavonol content in transgenic tomato peel by overexpression of the petunia *CHI* gene, indicating that the conversion of narengenein chalcone to narengenin is a rate-limiting step in flavonol biosynthesis in the peel and the overexpression of *CHI* alleviates a major bottleneck which causes a significant increase in the levels of the flavonols ([Muir et al. 2001](#_ENREF_18)).

Heterologous overexpression of *Del* and *Ros1* (*DR*) in tomatoes increases the activity of endogenous *CHI*, but not sufficiently to resolve the bottleneck ([Butelli et al. 2008](#_ENREF_2)). Since CHI is a major rate-limiting step in flavonol biosynthesis, we hypothesize that co-expressing *CHI* in the *DR*-expressing transgene tomato lines is necessary for full utilization of the anthocyanin and flavonol production pathway. In this study, *CHI* from onion (*Allium cepa* L.) was isolated and transformed to generate *CHI/DR*-co-expressing tomato plants. The stacked lines exhibit significant increases in both flavonol and anthocyanin content in both the peel and the flesh. The sustained growth of *CHI/DR-*co-expressing tomatoes demonstrates the potential of this biotechnology in tomato nutritional improvement with high antioxidant activity could help supplement a healthy diet to lower the risk of cancer, cardiovascular disease, diabetes, and promote healthy brain function.

Material and Methods

**Vector construction**

*CHI* gene was cloned from red onion (accession number, AY700851.1) ([Kim et al. 2004](#_ENREF_8)). RNA was extracted using an RNeasy plant mini-kit from QIAGEN (Valencia, CA, U.S.A). cDNA was made with the Advantage RT-for-PCR Kit from Clontech (Mountain View, CA, U.S.A). The primer sequences for *CHI* were forward 5' -ATGGAAGCAGTGACAAAGTT -3', reverse 5'-T CATGAAAGCACCGGTAACT-3'. The PCR product was inserted to pE1775 expression vector ([Lee et al. 2007](#_ENREF_12)) . The pE1775 vector harboring *CHI* gene was transferred to *Agrobacterium* (LBA4404) using the freeze-thaw method ([Holsters et al. 1978](#_ENREF_7)). The Del/Ros1 vector harboring *Del/Ros1* gene was used for this study ([Butelli et al. 2008](#_ENREF_2)).

**Plant transformaton**

Seeds of the *Solanum lycopersicum* L. (cv Rubion) tomato were surface-sterilized and germinated on a Murashige and Skoog inorganic salt medium ([Murashige and Skoog 1962](#_ENREF_19)). Tomato transformation was performed via the *Agrobacterium*-mediated transformation method using cotyledon and hypocotyl explants as described in ([Park et al. 2003](#_ENREF_22)). *Agrobacterium tumefaciens* LBA4404 was used in generating stable transgenic plants. The plasmids containing *CHI* and *Del/Ros* were introduced into *A. tumefaciens* using the freeze-thaw method ([Holsters et al. 1978](#_ENREF_7)). Following inoculation with *A. tumefaciens*, the plant cultures were maintained at 25 ˚C under a 16-h photoperiod. After 6 to 8 weeks, regenerated shoots were transferred to a rooting medium for 6 additional weeks. The greenhouse temperature was maintained within a range of 25 ˚C to 30 ˚C ([Lim et al. 2014](#_ENREF_16)).

**Molecular analysis of transgenic plants**

Tomato genomic DNA and RNA were extracted from leaf tissue with the Qiagen Plant DNA extraction kit. Tomato RNA was extracted from the peel and flesh with the Qiagen Plant RNA extraction kit. cDNA was synthesized using moloney murine leukaemia virus-reverse transciptase (BD Biosciences Clontech, Palo Alto, CA, USA). All polymerase chain reactions (PCR) were performed with a GoTaq Flexi DNA Polymerase kit (Promega Corporation, Madison, WI, USA).

**HPLC analysis**

One gram of peel was frozen in liquid nitrogen and macerated in a 15 ml round-bottom tube with a plastic pestle. The samples were hydrolyzed with 4.8 ml of 62.5% methanol and 1.2 ml 6M HCl for 60 min at 45˚C. The extracts were cooled on ice and sonicated at temperature for 45 min and then centrifuged at 13,000 RPM for 20 min. Supernatant filtering was performed with a 0.45 μm filter. The extraction procedure was following ([Muir et al. 2001](#_ENREF_18)).

HPLC analysis was modified from ([Oh et al. 2009](#_ENREF_20)). The HPLC system includes an autosampler (SpectraSYSTEM AS1000, Thermo Separation Products, San Jose, CA, USA), a pump (HP 1050, Hewlett Packard, Palo Alto, CA, USA), an integrator (HP 3396, Hewlett Packard, Palo Alto, CA, USA), and a UV/VIS detector (Acutect 500, Thermo Separation Products, San Jose, CA, USA). A 5 μL sample was injected into the HPLC column (Discovery BIO Wde Bore C18, 15 cm x 4.6 mm, 5 μm, Supelco, Inc., Bellefonte, PA, USA) with a guard column (Discovery BIO Wide Bore C18, 2cm x 4mm, 5 μm, Supelco, Inc., Bellefonte, PA, USA). The sample was eluted with eluant A [H2O/ CH3COOH (338/1, v/v)] and eluant B [H2O/C4H10O/CH3COOH (330/8/1, v/v/v)] at a flow rate of 1.8 mL/min. The gradient is A 20 ~ 20%, B 80 ~ 80%, 0~5 min: A 20 ~ 0%, B 80 ~ 100%, 5 ~ 25 min. Qualitative identification of flavonoid peaks was determined by co-chromatography (equivalent retention time) with chemically pure standards (5 mg/100 mL), and quantification was based on the integration of the peak area compared with a standard curve. The standards are quercetin-3-O-glucoside (Sigma–Aldrich, St. Louis, MO, USA), rutin (Sigma–Aldrich, St. Louis, MO, USA), Kaempferol rutinoside (Sigma–Aldrich, St. Louis, MO, USA), Quercetin (Sigma–Aldrich, St. Louis, MO, USA), Naringenin (Sigma–Aldrich, St. Louis, MO, USA), and Naringenin chalcone (Sigma–Aldrich, St. Louis, MO, USA).

**Total flavonoid and anthocyanin content**

For total flavonoid contents, the samples were measured prior to HPLC injection at 361 nm by a NanoDrop photospectrometer (Thermo Scientific, Wilmington, DE, USA). We used rutin as the standard.

We measured anthocyanin content with minor modifications ([Solfanelli et al. 2006](#_ENREF_26)). First, we ground tomato peels in volume HCl 0.5% (v/v) in methanol. An equal volume of chloroform was added to the extract to remove cholorphylls and the mixture was centrifuged for 1 min at 14,000g. Anthocyanins containing phase were recovered and absorption was determined spectrophotometrically at 544 nm with the NanoDrop. Delphinidin 3-Rutinoside was used as a standard (APin chemicals LTD, Abingdon, UK).

**Antioxidant activity**

We measured the antioxidant capacity of lettuce leaves using the modiﬁed 2, 20 -azino-bis (3-ethylbenzthiazoline-6-sulphonic acid) or ABTS method [25, 29, 30]. Antioxidants were extracted with a 5 ml extraction solution [methonal/ethanol (70/29.5/0.5, v/v/v)] from 1 g tomato peel and flesh samples. We incubated the antioxidant-containing extract in darkness overnight at -20˚C. Subsequently, we centrifuged the solution at 1000 rpm for 2 min. An ABTS [(2.5 mM) (Roche Diagnostics, Indianapolis, IN, USA)] stock solution was prepared and approximately 0.4 g of MnO2 (Acros Organics, Belgium) was added to the stock solution to generate ABTS radical cation (ABTS\*). Excessive MnO2 was removed using a 0.2 mM disk ﬁlter (Millipore Corp., Bedford, MA, USA). The ABTS\* solution was then incubated in a 30˚C water bath and was diluted to an absorbance of 0.7 at 730 nm using a 5 mM phosphate buffer saline solution [pH 7.4 and ionic strength (150 mM NaCl)]. We then added 100 μL of the extract added to 1 mL of the ABTS\* solution and vortexed for 10 s. Mixture absorbance was measured at 730 nm in a spectrophotometer (U-1100, Hitachi Ltd. Japan) after a 1-min reaction period. Trolox [(6-hydroxy-2, 5, 7, 8-tetramethylchroman-2-carboxyl acid) (Acros Organics, Belgium)] standard curve was prepared using a 0.5 mM stock solution.

**Lycopene analysis**

Lycopene analysis was modified from ([Levin et al. 2003](#_ENREF_13); [Yodjun et al. 2011](#_ENREF_29)). Lycopene was extracted from the peel and flesh tissue of fresh red-ripe fruits. The peel was macerated to a powder in liquid nitrogen with a mortar and pestle. The flesh tissue was minced to a puree in a mortar and pestle. The extraction buffer consisted of n-hexane:isopropanol:acetone (2:1:1) and contained 0.05% BHT. The 1 g sample was stirred with 5 ml of an extraction buffer for 30 min in the dark. The extraction buffer consisted of a hexane:acetone:ethanol ratio of 2:1:1 (v/v/v) ([Yodjun et al. 2011](#_ENREF_29)). Spectrophotometric absorbance at 472 nm was used to calculate lycopene concentration. The lycopene standard was purchased from Sigma–Aldrich (St. Louis, MO, USA).

**Stacking genes by cross-pollination**

The anthers were removed from unopened flowers one day before anthesis. Before noon the next day, the pollen was collected with forceps from both CHI and DR plants. The emasculated flowers were pollinated with forceps. After pollination, the forceps were rinsed in a 70 % alcohol solution and wiped with a tissue to kill pollen for next use.

**Harvesting and growing condition**

The temperature was set to 28 ºC in the day and 24 ºC at night. The plantlets were potted in 4 gallon plastic pots with soil, Metro-Mix 700 medium (Sun Gro Horticulture, Agawam, MA). All the plants were pruned to have 3-4 branches. The 2 ~ 3 fruits were pooled to measure weight. The fruits were harvest in c.a. two month.

**Statistical analysis**

The statistical analysis for the categorical data was modified as described previously ([Lim and Earle 2008](#_ENREF_14); [Lim and Earle 2009](#_ENREF_15)). The ANOVA (Analysis of variance) model was used. The analyses were performed using the GLM procedure ([SASInstitute 2004](#_ENREF_23)). The interaction between the genes and the line was considered for the SAS model. The mean separation was performed by Tukey test.

Results

**Generation of *CHI*- and *DR*-expressing tomato plants**

More than 10 independent transgenic lines were generated from *CHI and Del/Ros* constructs*,* separately, and 2 - 3 morphologically normal and healthy lines were selected and subjected to further analysis. Prior to crossing to combine the genes, the segregation analysis was performed at T1 generation stage. The T1 lines showing 3:1 segregation ratio was chosen for further crossing to ensure the single transgene insertion. The segregation analysis was carried out on 100 mg⁄ L kanamycin selection medium and confirmed by reverse transcriptase (RT)-PCR analysis (Fig. 2). The F1 CHI x DR is defined as the generation crossed by both T1 transgenic plants. All the stacked and unstacked genes were stably transmitted to the next generations.

The shape and weight of all the transgenic and crossed tomatoes were indistinguishable from those of the wild type plants (Fig. 3 a, b, c, Fig. 4 and Table 1). Also, there was no significant differences in liking of color or texture between them and the flavor and overall liking of CHI tomatoes are marginally higher over DR and wild type ([Lim et al. 2014](#_ENREF_16)). All of the T0, T1 and T2 and F1 and F2 transgenic and crossed lines developed as many seeds as the wild type plants (Fig. 3b). The outer peel color of the transgenic DR and CHI/DR tomatoes were purple and indigo, respectively (Fig. 3a and Fig 4 c and d). Also, the flesh color of the CHI/DR tomato was conspicuously darker than that of the DR tomato (Fig. 3c). The colors of the anthocyanin extracted from the peel and the flesh showed similar tendency with the peel and flesh color (Fig. 3d).

**Total anthocyanin content in *CHI/DR*-expressing tomatoes**

There was approximately 100 times and 400 times more total anthocyanin content in the peel of the DR (T2) and CHI/DR lines (F1 and F2, Fig 5 a and b), respectively, as compared to wild type plants. There was approximately 120 times and 260 times more total anthocyanin content in the flesh of the DR and CHI/DR lines, respectively. The anthocyanin content was almost untraceable in wild type plants. There were no significant differences between different transgenic lines for each gene. All the CHI/DR lines exhibited significantly higher anthocyanin content than all the CHI or DR alone transgenic tomatoes in both the peel and the flesh. Further, there were no significant differences between F1 and F2 generation for both the peel and the flesh. The total anthocyanin content of the wild type and CHI lines were barely traceable in both the peel and the flesh. Addition of the *CHI* gene to DR lines approximately increased total anthocyanin content in peel 4 fold and in flesh 2 fold.

**Total flavonol content in *CHI/DR*-expressing tomatoes**

The total flavonol content exhibited considerable dynamic variation in both the peel and the flesh (Fig 5 c and d). For the peel, all the CHI/DR lines showed significantly higher flavonol content than the wild type and DR lines. The CHI-8 line has highest flavonol content than any other transgenic plants. The CHI-6 line has no significant flavonol differences with CHI/DR and it has higher flavonol content than DR and wild type lines. This implied that the substantial increase in total anthocyanin content might not occur at the expense of total flavonols.

Regarding the flesh, however, all the CHI/DR lines exhibited significant differences from all of the CHI and DR lines as well as the wild type plants. In flesh, the CHI/DR lines exhibited 150–200 times more total flavonol content than the wild type plants, and approximately 20–27 times and 40–48 times more than the CHI and DR lines, respectively. Addition of CHI to DR lines approximately increased total flavonol content 1.5 fold in peel and 2 fold in flesh.

**Flavonol composition of in *CHI*-, *DR*-, and *CHI/DR*-expressing tomatoes**

Quercetin-3-B-D glucoside (QBD) and Rutin are both glycosylated forms of quercetin, and Kaempferol-3-Rutinoside is the glycosylated form of Kaempferol. In tomato peel, the QBD content from high to low was: CHI > DR > DR/CHI > wild type tomato, the rutin content from high to low was: CHI > CHI/DR > DR > wild type tomato, and the quercetin content from high to low was: CHI/DR > DR > CHI > wild type tomato (Fig. 6). Although these three chemicals contain the same aglycon, the content of them was not the same from plant transformed with different genes. The quercetin content may have been left over from the glycosylation to QBD or rutin. The Kaempferol-3-rutisnoside (KR) content was highest in the CHI/DR lines, but the CHI and DR lines exhibited no differences between each other. CHI converts naringenin chalcone to naringenin. The ratio of naringenin chalcone vs. naringenin might indicate the efficiency of CHI as an indirect indicator of *CHI* expression. The content of these compounds in the DR and CHI/DR tomatoes exhibited variation among the lines. There was less naringenin chalcone than naringenin in the CHI tomato. Finally, the naringenin chalcone content of the CHI/DR lines fell between that of the CHI and DR lines caused by overexpression of the *CHI* gene in the CHI/DR lines during the pumping of the naringenin chalcone flux into naringenin. The naringenin content of the DR and CHI/DR lines was higher than in the wild type and CHI lines (Fig. 6).

Regarding the flesh, the QBD content of the CHI lines was significantly higher than that in the DR, CHI/DR, and wild type lines, but the CHI/DR line exhibited the highest rutin and KR content among all the transgenic lines (Fig. 7). Although quercetin, naringenin, and narigenin chalcone were detected in the peel, they were not detected in the flesh.

**Lycopene content and antioxidant activity in *CHI/DR*-expressing tomatoes**

In order to investigate whether *CHI*, *DR*, and *CHI/DR* expressing tomatoes affect lycopene production pathway, we measured total lycopene content. No significant differences of lycopene content were detected between any of the transgenic lines and the wild type fruit, and the color of the lycopene extracts in the wild type and transgenic plants was indistinguishable in both the peel and the flesh (Fig. 8a and b).

In the peel, a Trolox equivalent anti-oxidant capacity (TEAC) assay showed that all the CHI and CHI/DR lines exhibited 18–24 times more TEAC while DR increased by only 10 times as compared to wild type (Fig. 8c and d). Peels in CHI/DR lines exhibited more than twice antioxidant activity than DR only plants. In the flesh, the antioxidant capacity of the CHI/DR lines was significantly higher than that in the single-gene transgenic plants, CHI and DR. TEAC is 45% higher in flesh tissue of DR/CHI plants than in the same tissues of DR only expressing plants (DR-11). Other lines have 27-42% increase by crossing with CHI lines.

**Fruit yield measurements**

There was no statistical difference between lines in every gene and between genes for weight and numbers of fruit. The average of fruit weight and number of fruit which were harvested in given time were 49.1 (±5.03) and 36.9 (±5.97).

Discussion

In this study, we generated dark purple tomatoes with approximately 4-fold and 2-fold increases in the levels of anthocyanins in tomato peel and flesh, respectively, compared to the *DR*-expressing tomatoes after co-expression of *CHI* to the *DR*-expressing tomato plants (Fig 5a). This result suggests that the conversion of naringenin chalcone to naringenin, catalyzed by CHI, is still a bottleneck in the anthocyanin biosynthesis pathway, though DR in tomatoes induce the expression of endogenous *CHI*. In addition to increased anthocyanins, we also observed a significant increase in total flavonol content after the addition of *CHI* to *DR*-expressing lines (Fig 5c) in tomato peel. With respect to flavonol content in tomato peel, it seems the DR may have less impact on total flavonol accumulation than CHI alone lines, which was confirmed by comparing flavonol content from CHI and CHI/DR lines. It is probably due to the tendency of DR to shift the pathways towards anthocyanin production and away from other flavonol production.

Compared to peel tissue, it is hard to achieve substantial increase of anthocyanin content in flesh. However, Several groups reported flavonol increase in flesh by overexpressing some genes. Colliver (2002) ([Colliver et al. 2002](#_ENREF_4)) reported that concomitant expression of *CHI, CHS, F3H* and *FLS* in tomato flesh increases flavonol content. Overexpression of *CHI, CHS, and F3H* led to an increase of dihydrokaempferol, which is one major branch point between anthocyanins and flavonols. Overexpression of *FLS* ensured a major shift towards the flavonol pathway and an increase in kaempferol, a flavonol. Among the 4 genes, *CHS* plays key role for flavonol production in flesh. There was no report that *Del/Ros* could upregulate *CHS* or *FLS* ([Butelli et al. 2008](#_ENREF_2)). Interestingly, the flesh of our DR overexpressing tomatoes was visibly purple without upregulation of *CHS* and *FLS*, even though it can act as a reportedly bottleneck. This suggests that while *CHS* is an important bottleneck early in the pathway, it may not be as important as upregulation of genes dedicated to anthocyanin production such as *DFR, ANS, 3-GT*, and *5-GT* for increased anthocyanin content. That indicates there may already be sufficient substrate available for anthocyanin production after upregulation of *PAL, CHI*, and *F3H*. Our *CHI* gene produced a moderate increase in both flavonol and anthocyanin content in the flesh after stacking DR genes. Reportedly, the *DR* gene upregulates not only *CHI*, but also *PAL,* and *F3H*. These genes and our *DR/CHI* do not compete, instead, they work together. All these genes play a role in conversion of phenylalanine into flavonol precursors known as dihydroflavonols. Dihydroflavols occur at the branching point between anthocyanin and flavonols.

([Butelli et al. 2008](#_ENREF_2)) reported that *CHI* activity approximately doubled in the turn/ripe state. Compared with *PAL* activity upregulated by *DR*, this increase in *CHI* activity is insufficient to fully reap the benefits of an upregulated PAL. Luo (2008) reported a similar situation that the content of rutin and kaempferol rutinoside showed no obvious differences between them even though the *AtMYB12* gene upregulated *F3’H* to move the flux from dihydrokaempferol to dihydroquercetin (Figure 1). In our experiment, the flavonol rutin is the most abundant flavonol in all wild type, *CHI*, *DR*, and *CHI/DR* lines. *DR* upregulates *F3’5’H*, which converts dihydrokaempferol to dihydromyricetin. This causes a competition between rutin production and anthocyanin production. Dihydrokaempferol is a common substrate of *FLS, F3’H*, and *F3’5’H* (Fig 1). Despite the competition for the common substrate, the *DR* and *CHI/DR* lines exhibit the highest rutin content compared with other flavonols, which suggests that *CHI* overexpression provides more than enough substrate for one enzyme to fully utilize. One of the main anthocyanins in the *DR* lines is a delphinidin type of which the precursor is dihydromyricetin ([Butelli et al. 2008](#_ENREF_2)). Bovy et al. (2002) reported that in *Solanaceous* species, *DFR* prefers dihydromyricetin and will not utilize dihydrokaempferol as a substrate. Dihydromyricetin is the precursor to the delphididin-type anthocyanins located far upstream along the flavonoid pathway and utilizes *DFR* to move in that direction. This indicates that, while F3’5’H activity drastically increases anthocyanin production by providing ample substrate, its activity is not so high that all dihydrokampferol is converted to dihydromyricetin. Thus, there is still enough substrate available to be converted to dihydroquercetin and eventually rutin, which suggests that *CHI* overexpression provides ample substrate for significant increases in both flavonoid and anthocyanin production. We used an ethanol/methanol solution to measure antioxidant activity. The water extraction property of flavonoids poorly reflects the effect of rutin on antioxidant activity because rutin is insoluble in water. The wild type, and transgenic tomatos are a good source of lycopene and exhibit strong antioxidant activity ([Ozkan et al. 2012](#_ENREF_21)). Lycopene, including β-carotenoid, is hydrophobic, unlike most flavonoids. The lycopene content in all wild and transgenic lines exhibited no significant differences, implying that intrinsic antioxidant activity in tomatoes remains intact even if when achieving a substantial increase in soluble flavonols and anthocyanin.

Several strategies have previously been reported for increasing flavonoid content. Until now, all attempts to increase flavonoid levels have focused on one flavonol or anthocyanin end products. *Lc/C1* ectopic expression does not upregulate the *CHI* and *PAL* genes, but it results in a moderate increase in both flavonol and anthocyanin ([Bovy et al. 2002](#_ENREF_1)). *DR* upregulation only led to increased anthocyanin content ([Butelli et al. 2008](#_ENREF_2)). *AtMBY12* upregulates the genes that are necessary for flavonol production, except for *DFR*, which is the first step in anthocyanin production and results in increased flavonol production. By adding CHI to DR expressing tomato plants we achieved an increase in anthocyanin and total flavonol content by alleviating a major bottleneck and providing ample substrate for the increased production of both. Combining CHI and DR, all three genes to maximize the capacity of CHI results in 2 fold increase in both peel and flesh in DR only tomato without the expense of flavonol content which is competing for common precursor.

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