Identification of flavone phytoalexins and a pathogen-inducible flavone synthase II gene (SbFNSII) in sorghum

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Abstract

Following inoculation with the anthracnose pathogen Colletotrichum sublineolum, seedlings of the sorghum resistant cultivar SC748-5 showed more rapid and elevated accumulation of luteolin than the susceptible cultivar BTx623. On the other hand, apigenin was the major flavone detected in infected BTx623 seedlings. Luteolin was demonstrated to show strong inhibition of spore germination of C. sublineolum than apigenin. Because of their pathogen-inducible and antifungal nature, both flavone aglycones are considered sorghum phytoalexins. The key enzyme responsible for flavone biosynthesis has not been characterized in monocots. A sorghum pathogen-inducible gene encoding a cytochrome P450 protein (CYP93G3) in the uncharacterized CYP93G subfamily was identified. Transgenic expression of the P450 gene in Arabidopsis demonstrated that the encoded protein is a functional flavone synthase (FNS) II in planta. The sorghum gene was then termed SbFNSII. It is a single-copy gene located on chromosome 2 and the first FNSII gene characterized in a monocot. Metabolite analysis by liquid chromatography–tandem mass spectrometry (LC-MS/MS) in precursor ion scan mode revealed the accumulation of 2-hydroxynaringenin and 2-hydroxyeriodytol hexosides in the transgenic Arabidopsis plants. Hence, SbFNSII appears to share a similar catalytic mechanism with the licorice and Medicago truncatula FNSIs (CYP93B subfamily) by converting flavanones to flavone through the formation of 2-hydroxyflavanones.

Key words: Colletotrichum sublineolum, CYP93G3, flavones, flavone synthase II, sorghum.

Introduction

Flavones are a large group of flavonoid metabolites with different physiological functions in higher plants. Although flavones are generally colourless, they function to alter coloration in flowers by complexing with anthocyanin pigments (Goto and Kondo, 1991). Flavones also serve as antioxidants to protect plants from UV irradiation. In leguminous plants, flavones are important signal molecules for establishing symbiotic relationships with root nodulation bacteria. Luteolin was the first flavone known to induce nod gene expression in the diazotrophic bacterium Sinorhizobium meliloti (Peters et al., 1986), leading to the production of Nod factors which are essential for the root nodulation process. Silencing of flavone synthases in Medicago truncatula resulted in flavone-deficient roots with reduced nodulation after inoculation with the bacterium (J Zhang et al., 2007, 2009). In maize, the C-glycosyl flavone maysin is responsible for the insecticidal activity in silk tissues toward corn earworm (Rector et al., 2002). Several flavones were also shown to have activities against a variety of organisms, including plants, nematodes, molluscs, fungi, oomycetes, and bacteria (Martens and Mithöfer, 2005), and some of them may be considered as phytoalexins.

In addition to their important physiological roles in plants, flavones have been demonstrated to show significant pharmacological activities, elevating their importance as nutritional components in our diet. For example, luteolin is considered to have the potential for cancer prevention and therapy due to its ability to induce apoptosis, inhibit cell proliferation, metastasis, and angiogenesis, and sensitize tumour cells to therapeutic-induced cytotoxicity (Lin et al.,...
2008). Besides, luteolin is well characterized for its antioxidant and anti-inflammatory activities both in vitro and in vivo (Seelinger et al., 2008). Possible mechanisms for its different pharmacological properties include scavenging of reactive oxygen species (Lien et al., 1999), enhancement of endogenous antioxidants (Leung et al., 2006), reduction of nuclear factor-κB activities (Shi et al., 2004), inhibition of DNA topoisomerases I (Chowdhury et al., 2002) and II (Cantero et al., 2006), phosphatidylinositol 3-kinase (Bagli et al., 2005), promotion of the degradation of a transcription factor (STAT3) involved in inflammation (Selvendrian et al., 2006), as well as stabilization of the tumour suppressor p53 (Shi et al., 2007).

Biosynthesis of flavones begins with flavanones which are the precursors for all the major flavonoid classes (Fig. 1). In dicots, two distinct flavone synthase (FNS) enzymes, FNSI and FNSII, have been described. FNSI, a soluble Fe2+/2-oxoglutarate-dependent dioxygenase (DOX) restricted to members of Apiaceae, directly introduces a double bond between C2 and C3 in flavanones (Martens and Mithöfer, 2005). FNSI shows high sequence identity to flavanone 3-hydroxylase (F3H), another DOX enzyme which uses the same flavanone substrates. Results from site-directed mutagenesis strongly suggested that parsley FNSI was evolved from gene duplication of F3H, followed by functional diversification (Gebhardt et al., 2007). On the other hand, FNSII is a cytochrome P450, oxygen- and NADPH-dependent, and membrane-bound monooxgenase found in other flavone-accumulating dicot families including Leguminosae, Asteraceae, Plantaginaceae, and Lamiaceae (Martens and Mithöfer, 2005). All the characterized FNSII enzymes belong to the P450 CYP93B subfamily, and most of the recombinant proteins converted flavanone to flavone directly in enzyme assays. However, FNSII genes from the legumes Glycyrhiza echinata (licorice) and M. truncatula were found to encode enzymes with flavanone 2-hydroxylase activities, leading to the formation 2-hydroxyflavanones in vitro (Akashi et al., 1998; Zhang et al., 2007), and flavones were formed only after acid treatments. In addition to maysin in maize, flavone glycosides are constitutively accumulated in cereal crops such as wheat (Cavaliere et al., 2005) and rice (Shih et al., 2008). However, the enzymatic steps responsible for flavone biosynthesis are still not fully understood in monocots.

Sorghum, Sorghum bicolor (L.) Moench, is the fifth-ranking cereal in the world and it is a close relative of maize (Zea mays). The plant is a rich source of distinct phytochemicals such as dhurrin (Busk and Moller, 2002), sorgoleone (Czarnota et al., 2001), and 3-deoxyanthocyanidins (Snyder and Nicholson, 1990). The 3-deoxyanthocyanidins are a unique class of flavonoid phytoalexins synthesized by sorghum as an essential component of active defence mechanisms (Nicholson et al., 1987; Snyder and Nicholson, 1990; Lo et al., 1999). Recently a pathogen-inducible stilbene synthase gene was functionally characterized in sorghum (Yu et al., 2005). Subsequently, trans-piceid was detected in infected sorghum seedlings, but its role in defence appeared to be secondary toward the anthracnose pathogen Colletotrichum sublineolum (Yu et al., 2008). In continuous attempts to investigate the roles of secondary metabolites in sorghum disease resistance, the flavone aglycones luteolin and apigenin have been identified as new phytoalexin compounds in the present study. Subsequently, a sorghum pathogen-inducible P450 gene belonging to the

![Fig. 1. Biosynthesis of flavones from flavanones. Two FNS enzyme systems have been described in dicots for flavone biosynthesis. FNSI is a soluble enzyme while FNSII is a membrane-bound P450 enzyme. FNSI and most FNSII enzymes convert flavanones to flavones directly. The licorice and M. truncatula FNSII enzymes catalyse the conversion of flavanones into 2-hydroxyflavanones which can be converted to flavones on acid treatment in vitro. SbFNSII was found to have a similar catalytic mechanism in this study. Flavanone 3-hydroxylase (F3H) also uses flavanones as substrates, producing dihydroflavonols which are the precursors for flavonols, anthocyanins, and proanthocyanidins. Dotted lines indicate multiple reaction steps.](https://academic.oup.com/jxb/article-abstract/61/4/983/540314)
uncharacterized CYP93G subfamily first identified in the rice genome (Nelson et al., 2004) was isolated and characterized. Metabolite analysis in transgenic Arabidopsis overexpressing the sorghum gene demonstrated that the encoded protein is an FNSII enzyme having a catalytic mechanism similar to that of the licorice and M. truncatula enzymes.

**Materials and methods**

**Sorghum growth conditions and fungal inoculation**

Seeds of the sorghum cultivars (SC748-5 and BTx623) used in this study were former collections of the late Professor Ralph L. Nicholson of Purdue University (West Lafayette, IN, USA). Sorghum seeds were planted in rolls of germination paper and kept in the dark for 4 d as described previously (Lo et al., 1996). Etiolated seedlings with elongated mesocotyls were then inoculated with conidial suspensions of *C. sublineolum* at 3.0 × 10⁵ conidia ml⁻¹ with Tween-20 as a wetting agent (100 µl ml⁻¹). The inoculated plants were kept at 100% relative humidity at room temperature for 24 h.

**RNA experiments**

Total RNA was extracted from mesocotyl tissues (1.0 g) using the Trizol method (Invitrogen). DNase I-treated RNA samples (3 µg) were reversely transcribed by M-MLV reverse transcriptase (Promega). Primers CL590 (5′-CGCAAGACCACCGTCTTTTCG-3′) and CL592 (5′-GGTAGCTTTTCGTGCG-3′) were used for amplification of *ShFNSII*, while primers HEL794 (5′-GCGACCTTACCGACTACCTC-3′) and HEL795 (5′-AAATATCCGTCG-3′) were used for amplification of a sorghum actin gene. The 5′ and 3′ ends of the *ShFNSII* transcript were mapped based on the sorghum expressed sequence tag (EST) contig TC105061 using a rapid amplification of cDNA ends (RACE) procedure as described by the manufacturer (Roche Molecular Biochemicals). PCR amplifications were programmed as follows: pre-incubation (95 °C for 10 min), followed by 30 cycles of denaturation (95 °C for 30 s), annealing (55–58 °C for 30 s), and extension (72 °C for 1 min), and finally extended by an extension step at 72 °C for 7 min.

**Sequence analysis**

Sequences of the CYP93 family were retrieved from GenBank and aligned by the ClustalW method (www.ebi.ac.uk/clustalw). The alignment was used to perform phylogenetic analysis by the Neighbor-Joining method in the MEGA 4 program using default parameters (Kumar et al., 2004). The bootstrap values for nodes in the phylogeny tree are from 1000 replications.

**Generation of transgenic Arabidopsis plants**

The *ShFNSII* coding region was amplified from sorghum cDNA by the above PCR protocol using the primers CL659 (5′-GATGGATGCATCCGTGTTAC-3′) and CL660 (5′-CTATGGTGTGCGAATAC-3′). The PCR product was inserted between the cauliflower mosaic virus (CaMV) 35S promoter and nopaline 3′-terminator in the plasmid vector 103c-SK (E Lam, Rutgers University, NJ, USA). The resulting overexpression cassette was cloned into the binary vector pCAMBIA 1300 (CAMBIA, Canberra, Australia) which harbours the hygromycin resistance gene for selection of plant transformants. *Agrobacterium*-mediated transformation of the final construct into Arabidopsis (Col-0) wild type and *t6* mutants was performed by the floral dip method (Clough and Bent, 1998). The *t6* line (SALK_113904) was obtained from the Arabidopsis Biological Resource Center (Columbus, OH, USA). Harvested seeds were surface sterilized and germinated on Murashige and Skooge (MS) agar containing 3% (v/v) sucrose and 25 µg ml⁻¹ hygromycin (Sigma). Resistant seedlings were transplanted and placed in a growth chamber (22 °C; 16 h light, 8 h dark). To induce the endogenous flavonoid pathway, *T1* seeds were germinated on MS plates without nitrogen sources. Leaves (0.5–1 g) were collected for metabolite analysis after 7 d.

**HPLC-MS analysis of plant metabolites**

Plant tissues (0.5 g) ground to fine powder in liquid nitrogen were extracted in 100% HPLC-grade methanol (500 µl). For acid hydrolysis, an equal volume of 2 N HCl was added to the samples for incubation at 90 °C for 1 h. Filtered samples (10 µl) were injected onto a Agilent 1100 series HPLC system (Agilent Technologies, CA, USA) connected with an Eclipse XDB-C18 column (µm, 2.1 × 150 mm, Agilent Technologies). Separation was performed using a solvent system of 0.5% formic acid/water (v/v) (A) and 0.5% formic acid/methanol (B) with a linear gradient of 15–60% B over 20 min, then held at 60% B for 5 min and equilibrated at 15% B for 10 min. The flow rate was maintained at 0.2 ml min⁻¹ and the elution monitored by a diode-array detector (200–600 nm) in tandem with an API2000-QTRAP® quadrupole-linear ion trap mass spectrometer (Applied Biosystems/MDS Sciex, Concord, ON, Canada) operating in positive ionization mode. Enhanced full scan and product ion spectra in the mass range of m/z 150–1000 were acquired using parameters optimized for maximum sensitivities: curtain gas, 20 (arbitrary unit); collisionally activated dissociation gas, medium; ion spray voltage, 5300 V; capillary temperature, 350 °C; nebulizing gas (GS1), 60 (arbitrary unit); heating gas (GS2), 60 (arbitrary unit); declustering potential, 75 V; entrance potential, 10 V; collision energy, 40 V; collision energy spread, 5 V. For precursor ion scan (PIS) analysis of flavone and 2′-hydroxyflavanone O-glycosides, Q1 was operated at unit resolution and Q3 was operated at low resolution, and the mass spectra were obtained over a scan range of 150–1000 amu. MS² experiments were accomplished by raising the orifice bias potential to induce fragmentation in the lens region, mass-selecting the appropriate product ion in Q1, inducing its fragmentation in q2, and mass-analysing the second-generation product ions in Q3 via a linear ion trap. To scan for the known cereal flavone compounds in infected sorghum samples, an information-dependent data acquisition (IDA) protocol was performed. Quantification of flavones in the plant samples was achieved by liquid chromatography–mass spectrometry (LC-MS) operating in multiple reaction monitoring (MRM) mode. The transition reactions of apigenin (m/z 287.2 → 153.1) and luteolin (m/z 271.2 → 153.1) were monitored after LC separation, and the LC-MRM peak areas were used for concentration determination. Authentic standards of luteolin and apigenin (Sigma) were used for metabolite identification and quantification. Data acquisition, peak integration, and calculations were all interfaced to a computer workstation running the Analyst 1.4.2 software (Applied Biosystems/MDS Sciex).

In vitro spore germination assays

For germination assays, conidia were dislodged with water from the surface of *C. sublineolum* cultures growing on oatmeal agar, and filtered through a layer of cheesecloth to remove hyphae and debris. Spore suspensions (20 µl; 5.0 × 10⁶ ml⁻¹) containing different concentrations (5–50 µM) of either apigenin or luteolin (Sigma) dissolved in 3% ethanol (for improved solubility) were inoculated on the surface of plastic Petri plates. Control experiments were prepared by incubating the spores in 3% ethanol without the test compounds. After dark incubation at room temperature for 9–12 h, germination and appressorium formation was examined and counted under a dissecting microscope.
Results

Accumulation of flavone aglycones in infected sorghum seedlings

LC-MS/MS analysis was performed to investigate the differentially accumulated metabolites in the sorghum cultivar SC748-5 after inoculation with *C. sublineolum*. SC748-5 has been demonstrated to show stable resistance to the anthracnose pathogen across different geographical locations (Mehta *et al.*, 2005; Perumal *et al.*, 2009). The metabolite profile of methanol extracts prepared from infected seedlings revealed the accumulation of a flavone aglycone (Fig. 2A) which was not detected in uninoculated samples (data not shown). Under positive ionization mode, the compound eluted at 27.7 min generated an [M + H]+ ion at m/z 287, which is consistent with the molecular weight of a [luteolin + H]+ ion. Identification of the m/z 287 ion was confirmed by its MS/MS fragmentation pattern in comparison with that obtained for an authentic luteolin standard (Fig. 2B). The time-course accumulation of pathogen-inducible flavones in SC748-5 was then compared with that of a highly susceptible cultivar BTx623 (Fig. 2C). In SC748-5 seedlings, luteolin was first detected at 48 h after inoculation and continued to accumulate up to ~2 µg g⁻¹ tissue during the course of the experiment. In BTx623 seedlings, luteolin were detected at 72 h after inoculation and the level was considerably (~3-fold) lower compared with the SC748-5 seedlings. On the other hand, appreciable amounts of apigenin up to ~6 µg g⁻¹ tissue were found to accumulate in the BTx623 seedlings starting from 72 h after inoculation. Apigenin was identified by LC-MS/MS analysis in comparison with an authentic standard (data not shown).

Following the identification of luteolin and apigenin as pathogen-inducible metabolites in sorghum seedlings, we addressed the question of whether they may function as phytoalexins. *In vitro* bioassays were therefore performed to investigate their effects on spore germination of *C. sublineolum*. On hydrophobic surfaces, the conidia of *C. sublineolum* germinate with short germ tubes, and melanized appressoria are formed within 9–12 h. Luteolin was found to exhibit strong inhibitory effects on the fungal pathogen in a dose-dependent manner (Fig. 3). Thus, spore germination was reduced by almost 60% at 20 µM and by >80% at 50 µM luteolin. On the other hand, apigenin was considerably less effective than luteolin at all the concentrations examined (Fig. 3). Spore germination was reduced by <50% at 50 µM apigenin.

Identification of CYP93G3 as a pathogen-inducible gene in sorghum

To understand the enzymatic mechanism of flavone synthesis in sorghum, an attempt was made to identify putative FNS-encoding sequences in the public databases. Using the known FNSII sequences to blast search against the DCFI Plant Gene Index (http://compbio.dfci.harvard.edu/tgi/plant.html), several sorghum contiguous sequences annotated to encode cytochrome P450 enzymes were retrieved. Among them, the expression of TC105061 (831 bp) was found to be up-regulated in infected sorghum seedlings. RT-PCR analysis revealed that TC105061 transcripts were detected starting at 24 h after inoculation in the SC748-5 seedlings (Fig. 4). On the other hand, the expression was only detected at 48 h after inoculation in the BTx623 seedlings. In both cultivars, no basal levels of

![Fig. 2. Accumulation of pathogen-inducible flavones in sorghum seedlings. (A) LC-MS/MS detection of luteolin in methanol extracts prepared from SC748-5 seedlings after inoculation with *C. sublineolum*. The indicated peak with an m/z 287 ion was not detected in control plant samples (not shown). (B) The MS/MS spectrum of the m/z 287 ion is identical to that obtained for an authentic luteolin standard (not shown). (C) Time-course accumulation of luteolin and apigenin in infected SC748-5 and BTx623 seedlings. FW, fresh weight.](https://academic.oup.com/jxb/article-abstract/61/4/983/540314)
protein shows moderate sequence identity to the characterized. utmem.edu/rice.html). On the other hand, the sorghum et al. CYP93G subfamily (Nelson uncharacterized P450 proteins designated as members of the genome annotation), respectively. Both rice sequences are the rice sequences Os06g01250 and Os04g01140 (TIGR rice XP_002461286) revealed 69.7% and 53.1% identities with analysis of the encoded protein (NCBI accession Sb02g000220 and there are no introns present. Sequence the sorghum BTx623 genome (http://www.phytozome.net collected at the indicated time points (h) after inoculation. luteolin at the same concentration.

expression were recorded in uninfected seedlings (data not shown).

The full-length cDNA clone was then recovered by RACE experiments using RNA samples prepared from infected sorghum seedlings. The sorghum P450 sequence encodes a protein of 541 amino acid residues with a predicted molecular mass of 59.280 kDa and a calculated pI of 7.987. The encoded protein contains features that are highly conserved among cytochrome P450 enzymes, including the proline hinge region, the oxygen-binding pocket, and the most diagnostic haem-binding signature motif near the C-terminus (Supplementary Fig. S1 available at JXB online). The sequence was found to be located on chromosome 2 in the sorghum BTx623 genome (http://www.phytozome.net/cgi-bin/gbrowse/sorghum/). The assigned gene identifier is Sb02g000220 and there are no introns present. Sequence analysis of the encoded protein (NCBI accession XP_002461286) revealed 69.7% and 53.1% identities with the rice sequences Os06g01250 and Os04g01140 (TIGR rice genome annotation), respectively. Both rice sequences are uncharacterized P450 proteins designated as members of the CYP93G subfamily (Nelson et al., 2004; http://drnelson .utmem.edu/rice.html). On the other hand, the sorghum protein shows moderate sequence identity to the characterized FNSII sequences (members of the CYP93B subfamily) from Gerbera hybrida (CYP93B2, 39.3%), Antirrhinum majus (CYP93B3, 40.5%), Perilla frutescens (CYP93B6, 37.5%), M. truncatula (CYP93B10, 38.8%), and G. echinata (CYP93B1, 38.0%). A phylogeny tree was then constructed using the Neighbor–Joining method for the different CYP93 subfamily proteins. As shown in Fig. 5, the sorghum protein is closely related to the two rice (Oryza sativa) CYP93G sequences. Hence, the sorghum sequence was designated as CYP93G3, a new member in this subfamily (David Nelson, P450 Nomenclature Committee, personal communication). The soybean (Glycine max) CYP93A subfamily, which includes a pterocarpan 6a-hydroxylase involved in the later stage of isoflavonoid biosynthesis (Tian et al., 2008), is located on the same branch with the CYP93B sequences. On the other hand, the CYP93B subfamily proteins appear to be more distantly related to the sorghum and rice sequences.

Characterization of SbFNSII biochemical functions in transgenic Arabidopsis

To examine whether CYP93G3 is a functional FNS enzyme in planta, the sorghum coding sequence was overexpressed in transgenic Arabidopsis under the control of the CaMV 35S promoter. The Arabidopsis tt6 mutant, which is defective in the single-copy F3H gene, was chosen as the host for Agrobacterium-mediated transformation. F3H and FNS are competing enzymes using the same flavonone substrates (Fig. 1). A total of 13 primary transgenic lines (confirmed by PCR genotyping) were obtained and constitutive expression of the sorghum transgene was confirmed by RT-PCR analysis (data not shown). T1 seeds of more than five independent lines were germinated on MS medium deficient in nitrogen to induce the endogenous flavonoid pathway. As constitutively expressed secondary metabolites are often modified by O-glycosylation in plants, 10-day-old Arabidopsis seedlings were extracted in methanol followed by acid hydrolysis to release the flavonoid aglycones for LC-MS/ MS analysis. As shown in Fig. 6A and B, two distinct peaks corresponding to luteolin and apigenin were detected in all the transgenic samples analysed. Their identities were confirmed by LC-MS/MS analysis as described above. The sorghum gene was also transformed into Arabidopsis wild-type (Col-0) plants. Quantitative analysis revealed that lower amounts of both flavone aglycones were detected in the transgenic plant samples in the Col-0 background compared with those in the tt6 background (Fig. 6C).

The above results clearly demonstrated that CYP93G3 functions as an FNSII enzyme in planta, and thus the sorghum gene was named SbFNSII. In the legume species licorice and M. truncatula, FNSII enzymes were found to function through the formation of 2-hydroxyflavanone intermediates (Fig.1; Akashi et al., 1998; Zhang et al., 2007). As the acid treatment would convert 2-hydroxyflavanones to the corresponding flavones (Akashi et al., 1998; Zhang et al., 2007), an attempt was made to detect the presence of their O-glycosylated derivatives in non-hydrolysed
samples prepared from the transgenic *Arabidopsis* lines. LC-MS/MS analyses were then performed to scan for precursor ions of m/z 289 and m/z 305, which are consistent with the molecular weight of the protonated ions of 2-hydroxynaringenin and 2-hydroxyeriodictyol, respectively. As shown in Fig. 7A, the total ion chromatogram of the PIS of m/z 289 revealed the most distinct peak (M1, m/z 451) eluted at 18.6 min in the transgenic plant sample. The MS/MS spectrum of m/z 451 ion showed the diagnostic m/z 289 ion, indicating the loss of a hexosyl unit (162 Da) from the parent ion (Fig. 7B). An MS3 experiment of the m/z 289 daughter ion produced a fragmentation pattern (Fig. 7C, D) which was essentially identical to that reported previously for a [2-hydroxynaringenin + H]+ ion (Zhang et al., 2007). Similarly, the total ion chromatogram of the PIS of m/z 305 revealed the most distinct peak (M2, m/z 467) eluted at 16.87 min (Fig. 8A). The MS/MS spectrum of m/z 467 showed the m/z 305 daughter ion, also indicating the loss of a hexosyl unit (162 Da) (Fig. 8B). An MS3 experiment of the m/z 305 daughter ion generated a fragmentation pattern that is consistent with that predicted for a [2-hydroxyeriodictyol + H]+ ion (Fig. 8C, D). Hence, M1 and M2 could be conclusively identified as 2-hydroxynaringenin and 2-hydroxyeriodictyol O-hexosides, respectively.

LC-PIS analyses were also performed to detect the presence of flavone O-glycosides in the non-hydrolysed transgenic plant samples. Table 1 summarizes the different O-glycosides of apigenin and luteolin identified. In all cases, MS3 experiments were conducted for structural confirmation of the protonated flavone daughter ions. Taken together, the *SbFNSII*-overexpressing transgenic *Arabidopsis* lines were demonstrated to accumulate O-glycosylated derivatives of both 2-hydroxyflavanones and flavones. On the other hand, none of these flavonoid metabolites was detected in the non-transformed plant samples (data not shown).

**Discussion**

Phytoalexins are low molecular weight antimicrobial compounds produced by plants in response to infection or stress (Paxton, 1981; Nicholson and Hammerschmidt, 1992). In sorghum, the 3-deoxyanthocyandins represent a unique group of flavonoid phytoalexins important for defence against *C. sublineolum* (Snyder and Nicholson, 1990; Lo et al., 1999). The anthracnose pathogen can cause severe foliar damages and result in substantial yield loss (Thomas et al., 1996). Over the years, host plant resistance has remained the most effective strategy for control of this sorghum disease (Perumal et al., 2009). Frequently plants produce multiple structurally related defence metabolites during host–pathogen interaction (Kuc, 1995; Smith, 1996). As part of ongoing efforts to understand the biochemical basis of sorghum anthracnose resistance, luteolin and apigenin have been identified as new flavonoid phytoalexins in sorghum in this study.

The antimicrobial activities and health-beneficial properties of flavones are well documented (Martens and Mithöfer, 2005). In contrast, only a few examples of pathogen- or stress-inducible flavones in plants have been described. Both luteolin and apigenin were identified in soybean cotyledons following treatment with an elicitor prepared from *Diaporthe phaseolorum f. sp. meridionalis* (Modolo et al., 2002). In addition, a complex mixture of C-glycosylated flavone derivatives (cucumersins A and B, vitexin, orientin, isoorientin) were detected in cucumber leaves expressing induced resistance against the powdery
mildew fungus *Podosphaera xanthii* (McNally et al., 2003). Using LC-MS/MS analysis with an IDA protocol, the various flavone C-glycosides known to accumulate in cereal crops, such as maysin, isovitexin, isoorientin, and isoscoparin (Grotewold et al., 1998), were not detected in the present infected sorghum samples (data not shown). Instead, luteolin and apigenin aglycones were identified as the major flavone metabolites in the resistant (SC748-5) and susceptible (BTx623) cultivars, respectively, following inoculation with *C. sublineolum*. The elevated and more rapid accumulation of luteolin in the resistant cultivar strongly suggested that this compound plays an important role in defence against the anthracnose pathogen. In fact, luteolin showed dose-dependent inhibition on *C. sublineolum* spore germination while apigenin was considerably less effective over the same concentration range (Fig. 3). Consistent with this, luteolin has been demonstrated to show higher cytotoxicity than apigenin on a human oesophageal adenocarcinoma cell line (Q Zhang et al., 2009).

Previously, SC748-5 and BTx623 were found to show different 3-deoxyanthcyanidin phytoalexin responses (Lo et al., 1999). Thus, the resistant cultivar accumulated luteolinidin which was not detected in the susceptible cultivar after inoculation with *C. sublineolum*. Luteolinidin was shown to be more fungitoxic than apigeninidin (Nicholson et al., 1987) which was produced by infected BTx623 seedlings as the major 3-deoxyanthocyanidin. Luteolin and luteolinidin are 3′-hydroxylated flavonoids,
and the synthesis of both flavonoid compounds requires the enzyme activities of flavonoid 3′-hydroxylase (F3′H). A family of F3′H genes have recently been characterized in sorghum, and the pathogen-inducible F3′H gene was expressed at minimal levels in infected BTx623 plants (Shih et al., 2006). Hence, F3′H may represent a molecular component essential for anthracnose resistance in sorghum by generating those 3′-hydroxylated flavonoids that showed stronger in vitro inhibitory effects. Recent improvements in sorghum transformation efficiencies (Gao et al., 2005; Wang et al., 2007; Gurel et al., 2009) may allow routine transgenic analysis of candidate genes (e.g. F3′H) for disease resistance and other useful agronomical traits in the near future.

Following the identification of flavones in infected sorghum seedlings, it was demonstrated that ShFNSII is a pathogen-inducible gene encoding a functional FNSII enzyme in planta. Although many cereal crops are known to accumulate flavone metabolites, ShFNSII is the first example of a functional FNSII gene reported in a monocot. Expression of ShFNSII was induced earlier in SC748-5 than in BTx623 following inoculation (Fig. 4), consistent with the more rapid accumulation of luteolin in the resistant plants (Fig. 2). In addition, ShFNSII is a new P450 member (CYP93G3) belonging to the CYP93G subfamily. Cytochrome P450 enzymes are known to participate in a diverse array of biosynthetic and degradative pathways in plants, animals, and fungi (Schuler and Werck-Reichhart, 2003). In flavonoid metabolism, they are involved in the biosynthesis of anthocyanins and tannins, flavones, and the leguminous isoflavonoid phytoalexins (Ayabe and Akashi, 2006), and members of the same subfamily usually catalyse the same metabolic reaction. For example, cinnamate 4-hydroxylase (CYP73A) provides p-coumaroyl-CoA which is a key substrate required for the formation of all flavonoids. In addition, the flavonoid B-ring hydroxylation patterns are determined by the activities of flavonoid 3′,5′-hydroxylases (CYP75A) and F3′Hs (CYP75B). In the CYP93 family, isoflavone synthase (CYP93C) and dihydroxypterocarpan 6a-hydroxylase (CYP93A) are legume-specific enzymes involved in the biosynthesis of isoflavonoids (Ayabe and Akashi, 2006). Furthermore, the CYP93B subfamily consists of the FNSII enzymes from different dicot families. Hence, the CYP93G subfamily potentially represents the FNSII enzymes in monocots or at least in Poaceae. In addition to ShFNSII (CYP93G3) and the rice members CYP93G1 and CYP93G2, a number of EST sequences (400–900 bp) in maize (FL159302), barley (BE215500, GH208016), wheat (BE426428, CV763338), and sugarcane (CA141841) with >70% sequence identity to ShFNSII could be retrieved from the NCBI databases by tblastn searches. It remains to be elucidated whether these P450 homologous sequences also encode proteins with FNSII activities.
In this study, the biochemical function of SbFNSII was established by transgenic analysis in Arabidopsis. Different flavonoid metabolites are known to accumulate in this model plant, including flavonols, proanthocyanidins, and anthocyanins (Winkel-Shirley, 2001). However, flavones are not present in almost all cruciferous plants (including Arabidopsis), consistent with the absence of FNSI- or FNSII-encoding sequences in the Arabidopsis genome (Martens and Mithöfer, 2005). Thus, Arabidopsis represents a useful system for in planta analysis of the FNS transgene without any background flavone accumulation. Recently the parsley FNSI gene was engineered in Arabidopsis, but flavone accumulation occurred only after exogenous application of naringenin (Yun et al., 2008). In contrast, all of the transgenic Arabidopsis lines were found to accumulate apigenin and luteolin O-glycosides constitutively (Table 1). The flavonoid pathway in Arabidopsis can be activated under nitrogen stress (Dong et al., 2001), thus providing a range of substrates for the introduced flavonoid enzymes in the transgenic plants. Apparently the endogenous flavanones (naringenin and eriodictyol) were used as the physiological substrates for SbFNSII. This was more evident by the higher levels of flavone accumulation in the transgenic tt6 plants (Fig. 6C) in which the competing enzyme F3H is defective.

While most FNSIIs converted flavanones to flavones directly, the licorice and M. truncatula FNSIIs instead produced 2-hydroxyflavanones which could be converted to flavones after acid treatments (Akashi et al., 1998; Zhang et al., 2007). The different flavones and 2-hydroxyflavanones accumulated as a result of the SbFNSII activities in Arabidopsis.

**Table 1. List of flavone O-glycosides accumulated in transgenic Arabidopsis**

The metabolites were identified in non-hydrolysed extracts by LC-PIS analysis in positive ionization mode. The identities of the [flavone + H]+ ions (in bold) had been confirmed by their MS3 spectra.

| Precursor ion | Retention time (min) | MS/MS ions | Compound assignment         |
|---------------|----------------------|------------|-----------------------------|
| 611           | 13.0, 16.9           | 449, 287   | Luteolin di-O,O-hexosides   |
| 449           | 20.2, 22.9           | 287        | Luteolin hexosides          |
| 595           | 13.2, 16.3           | 433, 271   | Apigenin di-O,O-hexosides   |
| 433           | 17.2, 18.6, 22.3     | 271        | Apigenin hexosides          |

In this study, the biochemical function of SbFNSII was established by transgenic analysis in Arabidopsis. Different flavonoid metabolites are known to accumulate in this model plant, including flavonols, proanthocyanidins, and anthocyanins (Winkel-Shirley, 2001). However, flavones are not present in almost all cruciferous plants (including Arabidopsis), consistent with the absence of FNSI- or FNSII-encoding sequences in the Arabidopsis genome (Martens and Mithöfer, 2005). Thus, Arabidopsis represents a useful system for in planta analysis of the FNS transgene without any background flavone accumulation. Recently the parsley FNSI gene was engineered in Arabidopsis, but flavone accumulation occurred only after exogenous application of naringenin (Yun et al., 2008). In contrast, all of the transgenic Arabidopsis lines were found to accumulate apigenin and luteolin O-glycosides constitutively (Table 1). The flavonoid pathway in Arabidopsis can be activated under nitrogen stress (Dong et al., 2001), thus providing a range of substrates for the introduced flavonoid enzymes in the transgenic plants. Apparently the endogenous flavanones (naringenin and eriodictyol) were used as the physiological substrates for SbFNSII. This was more evident by the higher levels of flavone accumulation in the transgenic tt6 plants (Fig. 6C) in which the competing enzyme F3H is defective.

While most FNSIIs converted flavanones to flavones directly, the licorice and M. truncatula FNSIIs instead produced 2-hydroxyflavanones which could be converted to flavones after acid treatments (Akashi et al., 1998; Zhang et al., 2007). The detection of 2-hydroxyflavonone O-glycosides in the present transgenic Arabidopsis lines strongly suggested that SbFNSII shares a similar catalytic mechanism with the two legume FNSII enzymes. In the transgenic Arabidopsis plants, an unknown endogenous enzyme may cause the dehydration of some 2-hydroxyflavanones to flavones. Such conversion was observed in transformed yeast cells expressing an FNSII from M. truncatula (Zhang et al., 2007). The different flavones and 2-hydroxyflavanones accumulated as a result of the SbFNSII activities in Arabidopsis.
the transgenic lines were apparently modified by the endogenous flavonoid O-glycosyltransferases. On the other hand, since no 2-hydroxyflavanones or their derivatives were detected in the infected sorghum samples by LC-MS/MS analysis using the IDA protocol (data not shown), an effective enzyme that allowed the complete conversion of 2-hydroxyflavanones to flavone is likely to be present in sorghum. In fact, 2-hydroxyflavanones may serve as a common intermediate for the formation of flavone aglycones and flavone C-glycosides in cereal plants. Recently, a rice recombinant enzyme was demonstrated to convert C-glucosylate 2-hydroxyflavanones preferentially, but with negligible activities toward flavones (Brazier-Hicks et al., 2009). In addition, dehydratase activities converting 2-hydroxyflavanone C-glycosides to flavone C-glucosides were identified in both rice and wheat protein extracts (Brazier-Hicks et al., 2009). Apparently a dehydratase enzyme specific for the 2-hydroxyflavanone aglycons is instead required for the inducible flavone aglycone formation in infected sorghum seedlings. Further investigations to understand the complete enzymology of flavone biosynthesis in sorghum will be largely facilitated by the recent completion of the sorghum genome sequence (Sasaki and Antonio, 2009).

Supplementary data

Supplementary data are available at JXB online.

Figure S1. Sequence alignment of CYP93G and selected CYP93B proteins by the ClustalW method. The putative proline hinge region (P), oxygen-binding pocket (O), and haem-binding motif (H) are boxed (SbFNSII = CYP93G3).

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References

Akashi T, Aoki T, Ayabe S. 1998. Identification of a cytochrome P450 cDNA encoding (2S)-flavanone 2-hydroxylase of licorice (Glycyrrhiza echinata L.; Fabaceae) which represents licodione synthase and flavone synthase II. FEBS Letters 431, 287–290.

Ayabe Shin-ichi, Akashi T. 2006. Cytochrome P450s in flavonoid metabolism. Phytochemistry Review 5, 271–282.

Bagli E, Stefaniotou M, Morbidelli L, Ziche M, Psillas K, Murphy C, Fotsis T. 2004. Luteolin inhibits vascular endothelial growth factor-induced angiogenesis, inhibition of endothelial cell survival and proliferation by targeting phosphatidylinositol 3’-kinase activity. Cancer Research 64, 7936–7946.

Brazier-Hicks M, Evans KM, Gershater MC, Puschmann H, Steel PG, Edwards R. 2009. The C-glycosylation of flavonoids in cereals. Journal of Biological Chemistry 284, 17926–17934.

Brusselmans K, Vrolix R, Verhovwen G, Swinnen JV. 2005. Induction of cancer cell apoptosis by flavonoids is associated with their ability to inhibit fatty acid synthase activity. Journal of Biological Chemistry 280, 5636–5645.

Busk PK, Moller BL. 2002. Dhurrin synthesis in sorghum is regulated at the transcriptional level and induced by nitrogen fertilization in older plants. Plant Physiology 129, 1222–1231.

Cantero G, Campanella C, Mateos S, Cortés F. 2006. Topoisomerase II inhibition and high yield of endoreduplication induced by the flavonoids luteolin and quercetin. Mutagenesis 21, 321–325.

Cavaliere C, Foglia P, Pastroini E, Samperi R, Lagana A. 2005. Identification and mass spectrometric characterization of glycosylated flavonoids in Triticum durum plants by high-performance liquid chromatography coupled with tandem mass spectrometry. Rapid Communications in Mass Spectrometry 19, 3143–3158.

Chowdhury AR, Sharma S, Mandal S, Goswami A, Mukhopadhyay S, Majumder HK. 2002. Luteolin, an emerging anti-cancer flavonoid, poisons eukaryotic DNA topoisomerase. Biochemical Journal 366, 623–661.

Clough SJ, Bent AF. 1998. Floral dip: a simplified method for Agrobacterium-mediated transformation of Arabidopsis thaliana. The Plant Journal 16, 735–743.

Czarnota MA, Paul RN, Dayan FE, Numal CI, Weston LA. 2001. Mode of action, localization of production, chemical nature, and activity of sorgholeone: a potent PSII inhibitor in Sorghum spp. root exudates. Weed Technology 15, 813–825.

Dong X, Braun EL, Grotewold E. 2001. Functional conservation of plant secondary metabolic enzymes revealed by complementation of Arabidopsis flavonoid mutants with maize genes. Plant Physiology 127, 46–57.

 Fang J, Zhou Q, Shi XL, Jiang BH. 2007. Luteolin inhibits insulin-like growth factor 1 receptor signaling in prostate cancer cells. Carcinogenesis 28, 713–723.

 Gao Z, Xie X, Ling Y, Muthukrishnan S, Liang GH. 2005. Agrobacterium tumefaciens-mediated sorghum transformation using a mannose selection system. Plant Biotechnology Journal 3, 591–599.

 Gebhardt YH, Whit S, Steuber H, Matern U, Martens S. 2007. Evolution of flavone synthase I from parsley flavanone 3-β-hydroxylase by site-directed mutagenesis. Plant Physiology 144, 1442–1454.

 Goto T, Konto T. 1991. Structure and molecular stacking of anthocyanins—flower color variation. Angewandte Chemie International Edition 30, 17–33.

 Grotewold E, Chamberlin M, Snook M, Siame B, Butler L, Swenson J, Maddock S, St. Clair G, Bowen B. 1998. Engineering secondary metabolism in maize cells by ectopic expression of transcription factors. The Plant Cell 10, 721–740.

 Gurel S, Gurel E, Kaur R, Wong J, Meng L, Tan HQ, Lemaux PG. 2009. Efficient, reproducible Agrobacterium-mediated transformation of sorghum using heat treatment of immature embryos. Plant Cell Reports 28, 429–444.

 Kuc J. 1995. Phytoalexins, stress metabolism, and disease resistance in plants. Annual Reviews of Phytopathology 33, 275–297.
Kumar S, Tamura K, Nei M. 2004. MEGA3: integrated software for molecular evolutionary genetics analysis and sequence alignment. *Brief Bioinformatics* 5, 150–163.

Leung HW, Kuo CL, Yang WH, Lin CH, Lee HZ. 2006. Antioxidant enzymes activity involvement in luteolin-induced human lung squamous carcinoma CH27 cell apoptosis. *European Journal of Pharmacology* 534, 12–18.

Lien EJ, Ren S, Bui HH, Wang R. 1999. Quantitative structure–activity relationship analysis of phenolic antioxidants. *Free Radical Biology & Medicine* 26, 285–294.

Lin Y, Shi R, Wang X, Shen HM. 2008. Luteolin, a flavonoid with potential for cancer prevention and therapy. *Current Cancer Drug Targets* 8, 634–646.

Lo SCC, de Verdier K, Nicholson RL. 1999. Accumulation of 3-deoxyanthocyanidin phytoalexins and resistance to *Colletotrichum sublineolum* in sorghum. *Physiological and Molecular Plant Pathology* 55, 263–273.

Lo SC, Weiergang I, Bonham C, Hipksind J, Wood K, Nicholson RL. 1996. Phytoalexin accumulation in sorghum: identification of a methyl ether of luteolinidin. *Physiological and Molecular Plant Pathology* 61, 179–188.

Martens S, Mithöfer A. 2005. Flavones and flavone synthases. *Phytochemistry* 66, 2399–2407.

McNally DJ, Wurms KV, Labbe C, Quideau Bélanger RR. 2003. Complex C-glycosyl flavonoid phytoalexins from *Cucumis sativus*. *Journal of Natural Products* 66, 1280–1283.

Mehta PJ, Wiltsie CC, Rooney WL, Collins SD, Frederiksen RA, Hess DE, Chisi M, TeBeest DO. 2005. Classification and inheritance of genetic resistance to anthracnose in sorghum. *Field Crops Research* 93, 1–9.

Modolo LV, Cunha FQ, Braga MR, Salgado I. 2002. Nitric oxide synthase-mediated phytoalexin accumulation in soybean cotyledons in response to the *Diaporthe phaseolorum* f. sp. *meridionalis* elicitor. *Plant Physiology* 130, 1288–1297.

Nelson DR, Schuler MA, Paquette SM, Werck-Reichhart D, Bak S. 2004. Comparative genomics of rice and Arabidopsis. Analysis of 727 cytochrome P450 genes and pseudogenes from a monocot and a dicot. *Plant Physiology* 135, 756–772.

Nicholson RL, Hammerschmidt R. 1992. Phenolic compounds and their role in disease resistance. *Annual Review of Phytopathology* 30, 369–389.

Nicholson RL, Kollipara SS, Vincent JR, Lyons PC, Cadena-Gomez G. 1987. Phytoalexin synthesis by the sorghum mesocotyl in response to infection by pathogenic and nonpathogenic fungi. *Proceedings of the National Academy of Sciences, USA* 84, 5520–5524.

Paxton JD. 1981. Phytoalexins—a working redefinition. *Phytopathologische Zeitschrift* 101, 106–109.

Perumal R, Menz MA, Mehta PJ, et al. 2009. Molecular mapping of *Cg7*, a gene for resistance to anthracnose (*Colletotrichum sublineolum*) in sorghum. *Euphytica* 165, 597–606.

Peters NK, Frost JW, Long SR. 1986. A plant flavone, luteolin, induces expression of *Rhizobium melloti* nodulation genes. *Science* 233, 977–980.

Rector BG, Snook ME, Widstrom NW. 2002. Effect of husk characters on resistance to corn earworm (*Lepidoptera: Noctuidae*) in high-maysin maize populations. *Journal of Economic Entomology* 95, 1303–1307.

Sasaki S, Antonio BA. 2009. Sorghum in sequence. *Nature* 457, 547–548.

Schuler MA, Werck-Reichhart. 2003. Functional genomics of P450s. *Annual Review of Plant Biology* 54, 629–667.

Seelinger G, Merfort I, Schempp CM. 2008. Anti-oxidant, anti-inflammatory and anti-allergic activities of luteolin. *Planta Medica* 74, 1667–1677.

Selvendiran K, Koga H, Ueno T, Yoshida T, Maeyama M, Torimura T, Yano H, Kojimo M, Sata M. 2006. Luteolin promotes degradation in signal transducer and activator of transcription 3 in human hepatoma cells: an implication for the antitumor potential of flavonoids. *Cancer Research* 66, 4826–4834.

Shi R, Huang Q, Zhu X, Ong YB, Zhao B, Lu J, Ong CN, Shen HM. 2007. Luteolin sensitizes the anticancer effect of cisplatin via C-Jun NH2-terminal kinase-mediated p53 phosphorylation and stabilization. *Molecular Cancer Therapy* 6, 1338–1347.

Shi R, Ong CN, Shen HM. 2004. Luteolin sensitizes tumor necrosis factor-alpha-induced apoptosis in human tumor cells. *Oncogene* 23, 7712–7721.

Shi CH, Chu H, Tang LK, Sakamoto W, Maekawa M, Chu IK, Wang M, Lo C. 2008. Functional characterization of key structural genes in rice flavonoid biosynthesis. *Planta* 228, 1043–1054.

Shi CH, Chu IK, Yip WK, Lo C. 2006. Differential expression of two flavonoid 3′-hydroxylase cDNAs involved in biosynthesis of anthocyanin pigments and 3-deoxyanthocyanidin phytoalexins in sorghum. *Plant and Cell Physiology* 47, 1412–1419.

Smith CJ. 1996. Accumulation of phytoalexins: defense mechanism and stimulus response system. *New Phytologist* 132, 1–45.

Snyder BA, Nicholson RL. 1990. Synthesis of phytoalexins as a site-specific response to fungal ingress. *Science* 248, 1637–1639.

Thomas MD, Sissoko I, Sacko M. 1996. Development of leaf anthracnose and its effect on yield and grain weight of sorghum in West Africa. *Plant Disease* 80, 151–153.

Tian L, Rang Y, Dixon RA. 2008. Biosynthesis and genetic engineering of proanthocyanidins and (iso)flavonoids. *Phytochemistry Reviews* 7, 445–465.

Wang W, Wang J, Yang C, Li Y, Liu L, Xu J. 2007. Pollen-mediated transformation of *Sorghum bicolor* biotypes. *Biotechnology and Applied Biochemistry* 48, 79–83.

Winkel-Shirley B. 2001. It takes a garden. How work on diverse plant species has contributed to an understanding of flavonoid metabolism. *Plant Physiology* 127, 1399–1404.

Yu CKY, Shih CH, Chu IK, Lo C. 2008. Accumulation of trans-piceid in sorghum seedlings infected with *Colletotrichum sublineolum*. *Phytochemistry* 69, 700–706.

Yu CKY, Springob K, Schmidt J, Nicholson RL, Chu IK, Yip WK, Lo C. 2005. A stilbene synthase gene (*SbSTS1*) is involved in host and nonhost defense responses in sorghum. *Plant Physiology* 138, 393–401.
Yun C-S, Yamamto T, Nozawa A, Tozawa Y. 2008. Expression of parsley flavone synthase I establishes the flavone biosynthetic pathway in Arabidopsis thaliana. Bioscience, Biotechnology and Biochemistry 72, 968–973.

Zhang J, Subramanian S, Stacey G, Yu O. 2009. Flavones and flavonols play distinct critical roles during nodulation of Medicago truncatula by Sinorhizobium meliloti. The Plant Journal 57, 171–183.

Zhang J, Subramanian S, Zhang Y, Yu O. 2007. Flavone synthases from Medicago truncatula are flavanone-2-hydroxylases and are important for nodulation. Plant Physiology 144, 741–751.

Zhang Q, Zhao XH, Wang ZJ. 2009. Flavones and flavonols exert cytotoxic effects on a human oesophageal adenocarcinoma cell line (OE33) by causing G2/M arrest and inducing apoptosis. Food and Chemical Toxicology 46, 2042–2053.