Promoter activity analysis and transcriptional profile of *Ginkgo biloba* 1-Deoxy-D- Xylulose 5-Phosphate reductoisomerase gene (GbDXR) under abiotic stresses

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Abstract

Terpene trilactones (TTL) is a pharmacological ingredient in *Ginkgo biloba* and its content has become one of the key indices for medicinal value evaluation of ginkgo. 1-Deoxy-D-xylulose 5-phosphate reductoisomerase (DXR) catalyzes the first step specific for isopentenyl diphosphate production in methylerythritol phosphate pathway, which provide the basic structure required for TTLs biosynthesis. To understand the mechanism controlling the *GbDXR* gene expression, the *GbDXR* promoter sequence was isolated and subjected to transient expression with the green fluorescent protein (GFP) in tobacco plants. Characteristic analysis revealed various cis-acting elements that related to light-regulated transcription, hormone signaling (auxin, ethylene), adversity stress and defense signaling (heat/dehydration stress) in the *GbDXR* promoter region. In transient expression assay, deletion of different portions of the upstream *GbDXR* promoter identified that the promoter region -3230bp to -865bp conserve the positive regulation function, which could promote the expression of GFP in the cytoplasm of tobacco leaf epidermal cells. The regulation function of the promoter region -865bp to -262bp remained to be elucidated. EMSA analysis suggested possible interactions of GbERF10 and GbERF17 with the ERF-binding elements in the upstream of *GbDXR* promoter. For abiotic stresses treatment, the expression of *GbDXR* gene could be significantly induced by UV-B and drought stress. In general, the *GbDXR* gene expressed differently in different ginkgo tissues but exhibited the highest transcriptional level in the root, with the maximum TTLs content simultaneously. The positive relationship between gene expression level and TTLs content indicated that the *GbDXR* is responsible for TTLs biosynthesis in *G. biloba*.

**Keywords:** DXR promoter; EMSA analysis; *Ginkgo biloba*; terpene trilactones; transient expression

**Abbreviation:** TTL-terpene trilactones; DXR-1-Deoxy-D-xylulose 5-phosphate reductoisomerase; GFP-green fluorescent proteins; IPP-isopentenyl diphosphate; DMAPP-dimethylallyl diphosphate; MEP-2-C-methyl-D- erythritol 4-phosphate pathway; MVA-mevalonate pathway; DXP-1-Deoxy-D-xylulose 5-
Introduction

Ginkgo biloba L. is a deciduous tree belongs to the division Ginkgophyta in gymnosperm with a very long surviving history, which commonly known as the "living fossil" that flourished during the Mesozoic Jurassic period 170 million years ago (Bowe et al., 2000; Uvackova et al., 2014). Although G. biloba is native to China, it has been transplanted worldwide as an ornamental and medicinal tree. Ginkgolides and bilobalide, collectively termed TTLs, are recognized as the medicinal ingredients uniquely exist in G. biloba (Strømgaard and Nakanishi, 2004). Their special pharmacological activities have been widely used in diseases treatment, such as reduce the symptoms of memory impairment and old-age dementia, treat the cardiovascular dysfunctions, prevent the vascular disorders and act as the platelet activating factor antagonist (Watanabe et al., 2001; Rodriguez et al., 2007; DeKosky et al. 2008). Though the TTLs content in G. biloba is low, it is an important index for quality evaluation and standardization of this medicinal materials. Increasing the biosynthesis and accumulation of TTLs through metabolic engineering and artificial planting would have practical significance in the improvement of G. biloba quality.

TTLs are highly modified diterpene lactones, and which are derived from the universal five carbon skeleton-isopentenyl diphosphate (IPP) and its isomer dimethylallyl diphosphate (DMAPP) (Cordoba et al., 2009). Higher plants use two pathways to form IPP and DMAPP, the methylerythritol phosphate (MEP) pathway in the plastid facilitates formation of monoterpenoids and diterpenoids, whereas the mevalonic acid (MVA) pathway in the cytosol facilitates the synthesis of sesquiterpenoids and sterols (Lange et al., 2000). It is inferred that the biosynthetic precursor of diterpenoid ginkgolides is expected to arise from the MEP pathway. In G. biloba, the ginkgolides were found present in both leaves and roots, however, genes coding for enzymes of the MEP pathway involved in IPP and DMAPP were highly expressed predominantly in the roots, which suggested that ginkgolides are synthesized in the roots and then transported to the stems and leaves (Kim et al., 2012).

As one of the structural genes involved in MEP pathway, 1-Deoxy-D-xylulose 5-phosphate reductoisomerase (DXR) catalyzes the critical step by converting 1-Deoxy-D-xylulose 5-phosphate (DXP) into 2-C-methyl-D-erythritol 4-phosphate (MEP), the first step specific for IPP production and which is the basic structure required for isoprenoids biosynthesis (Figure 1). Genes encoding DXR have been cloned and functional identified in G. biloba (Kim et al., 2006), however, there is little information about transcriptional regulation of GbDXR and no study has been reported regarding the promoter analysis of GbDXR.

Promoters are primarily located in the upstream region of genes with various specific cis-acting elements that can be recognized by transcription factors to regulate gene expression (Sazegari et al., 2015). In order to explore the physiological role and regulatory mechanism of GbDXR involved in TTLs synthesis, we isolated and functional characterized the promoter region of GbDXR, the promoter activity was preliminarily identified by promoter deletion analysis with the reporter gene transient expression in tobacco leaf epidermal cells. Furtherly, an interaction assay of AP2/ERF transcription factors with the cis-elements on the promoter of GbDXR was conducted using a EMSA technology. The expression pattern and functional analyses undertaken may contribute to understand the regulatory role of GbDXR promoter in TTLs biosynthesis in G. biloba.
Figure 1. The cytoplasmic MVA and plastidic MEP pathways in plants (Estévez et al., 2001)
The DXR gene catalyzes the step specific for IPP and DMAPP biosynthesis in MEP pathway. HMGR, hydroxymethylglutaryl-CoA reductase; FPP, farnesyl diphosphate; B1, thiamin; B6, pyridoxol; MECT, 2-C-methyl-D-erythritol-4-phosphate cytidylyltransferase; CMEK, 4-diposphocytidyl-2-C-methyl-D-erythritol kinase; MECPS, 2-C-methyl-D-erythritol-2,4-cyclodiphosphate synthase; GPP, geranyl diphosphate; GGPP, geranylgeranyl diphosphate

Materials and Methods

The different oligonucleotides used in this study were described as follows (Table 1).

Table 1. Genome walker and expression analysis primers of GbDXRP

| Description               | Serial number | Sequence (5’-3’) |
|---------------------------|---------------|-----------------|
| Genomewalker primers      |               |                 |
| AP1                       |               | GTAATACGACTCACAATATAGGGC |
| AP2                       |               | ACTATAAAGCACGCACGGTGGT |
| DXR1                      |               | GACCATCCACACACTTTTCTATCTCTCAT |
| DXR2                      |               | GTTCTATTTCTCATAAGCCC |
| DXR3                      |               | CTAGCTTTGAGATGTGAAGTCAACCA |
| DXR4                      |               | ACCTTATAAATCTCTCTTTTGCGTG |
| DXR5                      |               | TCAGGTCAATAGTAAAGTCACAACACAC |
| DXR6                      |               | GCGACTTTTGACAGTTACACAGAGA |
| Primers for DXRP1-5 amplification |       |                 |
| DPD                       |               | gtcag atcta ccargGACTTTGAGACAGTTAAGCAGAG |
| DPU1                      |               | cctct agatg caggAGGTCAATAGTTAAGGTCACAAACACA |
| DPU2                      |               | cctctagtagttagctTATGACTGTAAR TCTCACAAGATGTTCAAC |
| DPU3                      |               | cctctagtagttagcGACATGCTTACATCCACAGAGATGTTCAAC |
| DPU4                      |               | cctctagtagttagcTTGGATCATGTCTAGTGCTTCAAC |
| DPU5                      |               | cctctagtagttagcACTTATCATAAGGATAAGTTCGAG |
| Primers for verification  |               |                 |
| ZJ1                       |               | CCCAGGCTTTTACATTATGGCTC |
| ZJ2                       |               | TCAAAGAAGTGGACAGACAG |
| Primers for qRT-PCR       |               |                 |
| DXRF                      |               | CAGCAATAGAAGGGGAGAG |
| DXRR                      |               | ACCTTCTTGGTACACCTTGTGGC |
| GAPDF                     |               | GGGTGGGGGAGGG |
| GAPDR                     |               | CAACAGCAGACATGGGAGC |
Plant materials and treatments

Ginkgo leaves were obtained from the three-year-old seedlings (Ginkgo biloba L. cv ‘Jiafoshou’) grown in a greenhouse in Wuhan Polytechnic University. Tobacco (Nicotiana tabacum L. cv NC89) plants for Agro-infiltration were grown in a growth chamber at 25 °C in 16 h light (2000 lx)/8 h dark (16 L/8 D) for 45 days. Ginkgo seedlings with the same growth and development were subjected to UV-B, drought and ethylene (Eth) treatments. Samples under UV-B treatment were exposed to 1500 J/m² UV-B irradiation in a closed chamber, and the control group was placed in a dark chamber. For drought treatment, samples were collected as the relative water content decreased in soil, the whole dehydration stress lasted for 15 days. Eth (100 mg/L) was dissolved in 0.01% Tween 20 and sprayed onto leaves in experimental group, the leaves which were sprayed with the equivalent volume of 0.01% Tween 20 used as control. All samples were collected at different time point according to the arrangement. The harvested leaves were immediately frozen in liquid nitrogen and stored at -80 °C for DNA and RNA extraction.

Amplification of GbDXR promoter

Genomic DNA was extracted from leaf samples by an improved cetyltrimethylammonium bromide (CTAB) method described by Cheng et al. (2003). To obtain the 5’-upstream promoter sequence, specific primers were designed according to the cDNA sequence of GbDXR gene (AY494186, Kim et al., 2006) and the cloning was accomplished using the Universal Genome Walker kit (Clontech Laboratories, TaKaRa). First, the genomic DNA were digested by six restriction enzymes to build different genome walker libraries and which were used as the templates for PCR amplification, then two round PCR were performed continuous with the specific primers GbDXR1, AP1and GbDXR2, AP2 (Table 1). After three times of extension amplification, an approximate 3230 bp nucleotide sequence was obtained (Figure 2) and confirmed to be the GbDXR promoter (designated as GbDXRP) sequence by comparison analysis. The putative cis-elements and the transcription starting site of the GbDXRP were analyzed using the PLACE (http://www.dna.affrc.go.jp/PLACE) database and the Signal Scan Program PlantCARE.(http://bioinformatics.psb.ugent.be/webtools/plantcare/html/) database.

Construction of the GbDXR promoter: GFP plasmid

To identify regulatory regions involved in transcriptional control of the GbDXR gene expression, the cloned full-length GbDXRP1 together with it’s 5’-deletions GbDXRP2~GbDXRP6 were fused to GFP by replacing the CaMV 35S promoter in the vector pCAMBIA1304, respectively (Figure 3). The 5’-deleted promoter fragments were amplified by designing specific primers that contain PstI restriction site at the 5’-end of the forward primer and NcoI restriction site at the 5’-end of the reverse primer (Table 1), and ensuring that each fragment contains discrete elements of interest as can as possible. Therefore, six promoter fragments GbDXRP1 (-3230bp~+1bp), GbDXRP2 (-2562bp~+1bp), GbDXRP3 (-2024bp~+1bp), GbDXRP4 (-1457bp~+1bp), GbDXRP5 (-865bp~+1bp) and GbDXRP6 (-262bp~+1bp) were obtained using PCR and separately subcloned into pCAMBIA1304, of which the CaMV 35S promoter has already been removed by PstI and NcoI digestion. The fragments and linearized vector were linked by In-Fusion HD Enzyme Premix. The nucleotide sequencing results showed that all deletion constructs pCAMBIA1304+ GbDXRP1~GbDXRP6 were generated and prepared.
Figure 2. Nucleotide sequence (part) and some regulatory elements in *GbDXR* promoter are boxed.
Figure 3. Schematic diagram of the GbDXR promoter deletion sequences used for construction of fusion vectors

The pCAMBIA1304 vector was used as the positive control (A). The cloned full-length GbDXRP1 together with its 5'-deletions GbDXRP2-GbDXRP6 were linked to pCAMBIA1304 by replacing the CaMV 35S promoter respectively, the constructs were fused to the GFP reporter gene in the vector pCAMBIA1304 (B). pCAMBIA1304 without the 35S promoter (pCAMBIA1304-35SP) was taken as the negative control (C).

Agrobacterium-mediated transient expression of deletion constructs in tobacco plants

In our study, all deletion constructs including pCAMBIA1304-35SP (negative control) and pCAMBIA1304 (positive control) were transferred into the Agrobacterium tumefaciens LBA4404 based on the freeze/thaw procedure. Transformants were inoculated into 50 mL YEB plate supplemented with kanamycin (50 μg/mL) and rifampicin (40 μg/mL) and cultured at 28 °C for 48 h. The bacteria liquor was collected and resuspended in infiltration solution (1 mM Glucose, 500 mM MES, 20 mM Na₃PO₄·12H₂O, 1M acetosyringone) and adjusted to an OD₆₀₀ between 0.4-0.6 for transient expression assay.

Chose healthy tobacco plants and placed under the white fluorescent lamp for 1-2 h to fully open the stomatas of the leaves. The agroinfiltration at the abaxial surfaces of tobacco leaves with a needleless syringe was performed according to the protocol described by Sparkes et al. (2006). Then the tobacco plants were cultivated in a normal growth condition for up to 4 or 5 days for the fluorescence microscopy detecting.

Electrophoretic mobility shift assay (EMSA)

The putative ERF-binding elements in promoter sequence of GbDXR were predicted and identified as TGACY in characterization analysis (Table 2). Oligonucleotides of ERF-binding sequence were synthesized and the distrand DNA were separately labeled with biotin (Biotin 3' End DNA Labeling Kit, Pierce Biotechnology, Thermo Scientific) for non-isotopic detection. To synthetic probe, the complementary labeled strands were mixed together equal amounts and annealed at 25 °C after denaturation at 90 °C. Using a LightShift Chemiluminescent EMSA Kit (Pierce Biotechnology, Thermo Scientific), the binding reaction was performed by incubating 0.5 ng labeled probe, purified AP2/ERF protein and competing oligonucleotides in binding buffer (10 mM Tris-HCl, pH 7.5, 1 μg/μL poly (dl-dC), 50% Glycerol, 1% NP-40, 100 mM MgCl₂, and 200 mM EDTA) at room temperature for 20 min. Mixtures were electrophoresed on a non-denaturing polyacrylamide gel followed by drying and transferring into nitrocellulose membranes and detecting by Chemiluminescence for Biotin-labeled probes in a CCD camera.
Quantitative analysis of GbDXR transcription levels

The transcription level of GbDXR was detected by real-time quantitative PCR (qRT-PCR). The leaves have been through different treatments as well as those ginkgo tissues were collected for RNA extraction. We used PrimeScript® RT Reagent Kit (Dalian TaKaRa, China) to synthesize the First-strand cDNA and chose SYBR® Fast qPCR Mix (Dalian TaKaRa, China) to perform qRT-PCR reactions, all procedures were in strict accordance with the operation instruction. The primers for qRT-PCR were listed in Table 1 and the PCR reaction conditions were: 95 °C for 30 S, then 40 cycles (95 °C for 5 S, 60 °C for 15 S) of amplification. Each sample was amplified three times to keep the accuracy and all data were analyzed by IBM SPSS Statistics 21.

Determination of TTLs by HPLC-ELSD

Different ginkgo tissues were also collected for TTLs extraction, the content of ginkgolide A (GA), ginkgolide B (GB), ginkgolide C (GC), bilobalide (BB) were determined by HPLC-ELSD (Li and Fitzloff 2002). The chromatographic separation was achieved using an Agilent C18 column (5 μm, 4.6 mm × 250 mm) at 40 °C. The mobile phase was methanol: tetrahydrofuran: H2O (20:8:72) and the flow rate was 1 mL/min. The ginkgolide detection was accomplished using the evaporative light scattering detector (ELSD). Each test was carried out in triplicate.

Statistical analysis

All data were reported as means ± standard error (SE) and analyzed using the Statistical Product and Service Solutions (SPSS 21.0), if p < 0.05, the results would be viewed as the significant difference.

Results

Identification and characteristics of GbDXR promoter

The promoter region of GbDXR was isolated based on the constructed G. biloba Genome Walker DNA libraries and gene-specific primers designed from the coding sequence of GbDXR. A 3230 bp fragment containing 5′-upstream sequence of GbDXR was cloned, and bioinformatics analysis of partial of GbDXR promoter sequence was processed using the PlantCARE and the PLACE programs (Table 2, Figure 2). The putative transcriptional start site was located at 12 bp upstream from the ATG codon. The nearest basal TATA-box to the transcriptional starting site was located at -30 bp upstream and the CAAT-box was located at -107 bp, the total 12 TATA-box and 22 CAAT-boxs might suggest the strong initiation function of GbDXRP. Beyond the basal elements, the GbDXR promoter region also contains various important cis-acting elements that related to light-regulated, hormone signaling, adversity stress and defense signaling responsiveness. For example, the GATA-box (GATA), GT-element (GRWAAW) and Inr-element (YTCANTYY) are typical light-responsive elements (Perisic and Lam 1992; Aird et al., 1994; Noguchi et al., 1994), which indicated that the GbDXRP may be sensitive to light signaling. The NTBBF1 (ACTTTA) and ERF-binding (TGACY) are plant hormone regulation elements that can response to auxin and ethylene respectively (Altamura, 2004; Phillips et al., 2013). The elements like MYB-box (CNGTTR), MYC-box (CANNTG) and W-box (TGAC) are not only response to plant hormones (Auxin, Abscisic acid, Eth, et al) but also involved in plant defense signaling (Proudhon et al., 1996). Furthermore, the GbDXRP also contains high temperature resistance element, like HSE-element (CCAAAT), and the disease resistance element As-1 (TTTGAC) with three different locations in the promoter region. These varied putative cis-acting elements suggested that the transcriptional activity of the GbDXR promoter is regulated by diverse environmental signals.
Table 2. Cis-acting elements analysis of the promoter sequence from *Ginkgo biloba* DXR by PLACE

| Name of element | Motif sequence | Copy no. in promoter | Function |
|-----------------|----------------|----------------------|----------|
| TATA-box        | TATAA          | 12                   | Common cis-acting element in promoter and enhancer regions |
| GATA box        | GATA           | 14                   | light regulated, and tissue specific expression |
| GT-element      | GRWAAW         | 11                   | Consensus GT-1 binding site in many light-regulated genes |
| CAAT-box        | CAAT           | 22                   | Common cis-acting element in promoter and enhancer regions |
| Inr-element     | YTCANTYYY      | 6                    | Initiator; light-responsive transcription |
| ARR1-binding    | NGATT          | 5                    | response regulator, ARR1-binding element |
| E-box           | CANNTG         | 4                    | cis-element binding bHLH factor involved in light |
| T-box           | ACTTTG         | 2                    | Mutations in the ‘T box’ resulted in reductions of light-activated |
| AuxRE           | TAACAGA        | 1                    | auxin-upregulated proteinase expression |
| MYBCORE         | CNGTTR         | 6                    | MYB recognition site involved in dehydration-responsive |
| MYCATRD22       | CANNTG         | 15                   | Binding site for MYC, dehydration-responsive gene |
| DOF-binding     | AAAG           | 18                   | Transcription factors involved in carbon metabolism |
| SRE             | GAGAC          | 1                    | Sugar-responsive element |
| CURECORECR      | GTAC           | 4                    | Copper-responsive element |
| Root-motif      | ATATT          | 13                   | Root specific expression |
| W-box           | TGAC           | 15                   | WRKY binding site, involved in mang physiological processes |
| NTTBF1ARROLB    | ACTTTA         | 3                    | Required for tissue-specific expression and auxin induction |
| ERF-binding     | TGACY          | 12                   | May be involved in activation of ERF3 gene by wounding and |
| HSE-element     | CCAAT          | 3                    | Cis-acting element involved in heat stress responsiveness |
| As-1            | TTGAC          | 3                    | disease resistance |
| CATGTG motif    | CATGTG         | 3                    | drought-responsive cis-element in the early responsive to |

Deletion analysis of the GbDXR promoter in transgenic plants

To identify the regulatory activity of the GbDXR promoter and its deletions, six GFP fusion constructs were generated as the schematic diagram shown in Figure 3 and implemented to *agrobacterium*-mediated transient expression assay in tobacco leaves. The leaf epidermal cells were observed using the epifluorescence microscope (Nikon, Japan) about four days later after infiltration. The results showed that the epidermal cells and stomata could be seen clearly in 40 × eyepiece microscope under natural light (Figure 4A). When giving UV-B irradiation, the stomata and other organizations emitted red fluorescence, but the GFP emitted bright green fluorescence (Burchard et al., 2000). Figure 4B showed the result of the positive control vector pCAMBIA1304, the GFP were expressed normally and located in the cytoplasm of the epidermal cells. The GFP in fusion constructs pCAMBIA1304+GbDXRP1~P3 also expressed in the cytoplasm and emitted bright green fluorescence (Figure 4C-E), which predicted that the promoter sequence GbDXRP1 (-3230), GbDXRP2 (-2562) and GbDXRP3 (-2024) can promote the transient expression of GFP in tobacco epidermal cells. Following, the expression of GFP in fusion constructs pCAMBIA1304+GbDXRP4~P6 were continue detected, the results showed that GbDXRP4 (-1457, Figure 4F) and GbDXRP5 (-865, Figure 4G) still retained the promoter activity and the GFP expressed with relative high levels, but no green fluorescence could be observed in GbDXRP6 (-262, Figure 4H). pCAMBIA1304 vectors without the 35S promoter (pCAMBIA1304-35SP) were the negative control in this assay, the GFP could not expressed and only the red fluorescence could be observed (Figure 4I).
Figure 4. Expression of GFP in tobacco leaf epidermal cells detected by epifluorescence microscope

Under nature light, the leaf epidermal cells could be observed clearly at 40× objective (A). Scale bar, 10 μm, the black arrow points to the stomata; The result of the positive control pCAMBIA1304 showed that the GFP expressed and emitted green fluorescence when giving UV-B irradiation (B). Scale bar, 10 μm, the black arrow points to the stomata; The promoter sequences GbDXRP1–GbDXRP5 could promote the expression of GFP respectively, the bright green fluorescence could be observed in the cytoplasm of epidermal cells (C–G). Scale bar, 10 μm; The GbDXRP6 could not initiated the expression of GFP and no green fluorescence could be observed (H). Scale bar, 10 μm; In the negative control pCAMBIA1304-35SP, the GFP also could not expressed and only the red fluorescence emitted by other organizations (I). Scale bar, 10 μm

EMSA assay of GbDXRP with AP2/ERF transcription factors

Characteristic analysis showed that there are at least 12 putative ERF-binding elements in GbDXR promoter sequence, to confirm whether the ERFs proteins could interact with these cis-acting elements, the labeled ERF-binding probe together with ERFs proteins were subjected to EMSA assay. Two AP2/ERF transcription factors GbERF10 and GbERF17 from G. biloba transcriptome data have already been cloned and which might be related to TTLs biosynthesis. The overexpression of these two ERFs genes were induced by isopropyl-β-D-1-thiogalactopyranoside (IPTG) in E. coli respectively. After purified and detection, the molecular weight of ERFs proteins was estimated to be 40–55 kDa with His-tag, and their size agreed with that of the predicted peptide from bioinformatics analysis. The interaction between GbERFs and the GbDXR promoter sequence were assayed with EMSA. GbERF10 and GbERF17 specifically bound with ERF-binding elements (Figures 1, line 1 and 2). No binding bands were detected with crude proteins of E. coli without or with the empty vector pET-28a (Figures 5, line 3 and 4), and unlabeled probes competitively inhibited the binding (Figures 5, line 5 and 6). The results preliminary confirmed that GbERF10 and GbERF17 proteins can combine with the ERF-binding elements in GbDXR promoter sequence.
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**Figure 5.** Gel mobility shift assays of the binding reactions in EMSA detection
1,2 is the recombinant GbERF10 and GbERF17 mixed with Biotin-labeled ERF-binding probe, respectively; 3 is *E. coli* protein mixed with Biotin-labeled ERF-binding probe; 4 pET-28a protein mixed with Biotin-labeled ERF-binding probe; 5,6 GbERF10 and GbERF17 mixed with Biotin-labeled and unlabeled ERF-binding probes, competitively inhibiting.

**Figure 6.** Quantitative analysis of *GbDXR* transcription levels in response to A: UV-B, B: Drought, C: Eth Relative quantities of *GbDXR* mRNA at different time point in each sample was assayed in triplicate (*n*=3). Values are the mean of three treated plants and bars represent the standard errors. The asterisk along the x-axis represents statistically significant differences of mean (*p*<0.05; **p**<0.01)
Changes of GbDXRP transcript level to UV-B, drought stress and Eth stimulants in Ginkgo

In this study, we used UV-B, drought and Eth at different concentrations to treat ginkgo leaves, and explore the GbDXR transcription level change regulated by external environment via GbDXRP (Figure 6). The transcription level of GbDXR was tested at 12, 24, 48, and 72 h under the UV-B treatment, the results of qRT-PCR showed that the highest transcription level of GbDXR appeared at 48 h after treatment, and then declined at 72 h (Figure 6A). The drought stress lasted for 15 days, the continuous dehydration led to an abnormal expression of GbDXR, the transcriptional level of GbDXR was increased obviously and reached maximum after drought treatment for 10 d. However, as the degree of drought increased, the transcriptional level of GbDXR slowly declined (Figure 6B). The effect of Eth treatment on the expression of GbDXR was not significant, the transcriptional level increased slightly after 3 d of treatment (Figure 6C). The changes of the transcriptional level in different abiotic stresses indicated that the UV-B and drought stress could significantly induce the expression of GbDXR.

TTLs content in ginkgo tissues and the relationship with the expression of GbDXR gene

Previous research showed that GbDXR retained a higher transcription level in roots than in leaves and the TTLs content in these two tissues were different (Kim et al., 2006). Here, we extended the expression pattern analysis of GbDXR to additional tissues of ginkgo via qRT-PCR. The TTLs content in these tissues were measured simultaneously using the HPLC-ELSD detection (Figure 7). Figure 7 showed the changes of the transcript level of GbDXR and TTLs content in all tissues, including the roots, stems, leaves, fruits, male and female flowers. Similarly, the highest transcript level of GbDXR was in the roots and with the maximum total triterpenoids content $5.3635 \pm 0.0862 \text{ mg/g}$. In male flowers, though the total triterpenoids content was 40% higher than leaves, the transcript level of GbDXR was slightly lower. The total triterpenoids content in female flowers was similar to the stems, but the transcript level of GbDXR in these two tissues was different.

The linear regression analysis was carried out to study the relationship between the GbDXR expression levels and the TTLs content in these tissues. The GbDXR transcript level was taken as the independent variable ($x$) while the total triterpenoids content was the dependent variable ($y$), the linear curve equation represented as $y = (0.9124 \pm 0.0036)x + (0.5312 \pm 0.0887)$, $R^2 = 0.695$ (Figure 8). The relatively high linear correlation coefficient ($R^2$) suggested the positive correlation between the GbDXR expression and the TTLs content and which indicated that the biosynthesis of total terpenoids correlate with the changes of GbDXR transcript levels.

![Figure 7](image)

Figure 7. The relative transcript level of DXR and the diverse distribution of TTLs content in different ginkgo tissues
Previous research showed that the gene expression is regulated by the cis-elements in its promoter region (Guan et al., 2000; Yamaguchi et al., 2005). The GbDXR also contains various cis-elements that can respond to light signaling, temperature, plant hormones, dehydration stress, and disease resistance. Some cis-elements were predicted to make the corresponding reaction to multiple environmental stimulants. In particular, by responding of these specific elements to the changes of environment, the transcripts of those structural genes may be promoted or inhibited since to affect the synthesis of some secondary metabolites, the products that can mitigate the stress-damaged start to accumulate and provide the instant protection for plants. The secondary metabolites like anthocyanins, flavonoids are scavenger compounds of plants under adverse conditions (Yang et al., 2012).

We chose the transient expression in tobacco plants to detect the promoter activity of GbDXRP. The GbDXR′ region was examined through a series of 5′ deletions translationally fused to the GFP reporter gene. The result showed that the series of deletions from -3230 to -865 can promote the expression of the GFP when the stable genetic transformation was generated, but the further deletion -262 nearly terminated the activity, which suggested that the region from -865 to the initiation codon is sufficient for promoter activity. However, the regulation function of the promoter region from -865 to -262 remained to be elucidated. Tebbutt et al. (1995) reported that in the deletion analysis of a tobacco pollen-specific polygalacturonase promoter, the two LAT52/56 motifs and the PG box undertake the promoter function in the sequence. Therefore, further study is needed to find these critical regulatory elements in GbDXR promoter sequence.

UV-B radiation is an important factor enhancing the production of secondary metabolites in plants. Takshak et al. (2014) found that the concentrations of alkaloids, anthocyanins, carotenoids, flavonoids, lignin, phytosterols and saponins were generally increased in Withania somnifera under supplemental UV-B radiation. The similar results depicted in Chrysanthemum morifolium (Si et al., 2015), Dendrobium officinale (Guo et al., 2016), Eucommia ulmoides (Fu et al., 2017), and many other medicinal plants. In our study, the UV-B treatment could rapidly improve the expression of GbDXR, indicating that the TTLs content increased and might act as protective compounds accumulate in G. biloba, the result is consistent with the studies of Vranová et al. (2012). Under the induction of UV-B radiation, some transcription factors might activate the promoter of GbDXR, and positive regulated the expression of GbDXR gene. Accumulation of metabolites often occurs when plants suffer from environmental stresses (Akula and Ravishankar, 2011), the drought stress,
as one of the common environmental stresses, it’s effect on secondary metabolites has already been reported in several medicinal plant species. Hao et al. (2007) have detected the TTLs content in G. biloba under different drought phases, the TTLs content has no obvious change under mild drought stress, as the water content declined to moderate stress, the TTLs content increased and accumulated significantly, but when the water content was less than 20%, the content of TTLs declined obviously. Here, the transcriptional level of GbDXR exhibited the similar changes to drought stress, we presumed that the GbDXR regulate the synthesize of TTLs by responding to drought stress via GbDXRP. Additionally, many specific dehydrations stress responsive elements are imbedded in GbDXR promoter sequence, including 15 MYCATRD22 (CANNTG) and 3 CATGTG motif (CATGTG) (Kasuga et al., 1999), which suggest that the GbDXR gene can response to drought stress sensitively. Together with the result of drought treatment to ginkgo leaves in Zhang’s (2005) report, we concluded that moderate dehydration stress may help us to obtain ginkgo leaves with relative higher TTLs content. Studies found that in ethylene-responsive genes promoter region, the GCC box cis-acting elements specifically response to Eth (Pirrello et al., 2012). In addition, the vascular wounding responsive elements were also demonstrated to be the Eth responsive elements (Sasaki et al., 2007). It has been reported that the Eth could improve the yield of rubber latices in Hevea brasiliensis (Duan et al., 2010). Though the Eth could also induce the expression of GbDXR to a certain degree, it’s effect on the TTLs content in G. biloba was not significant. EMSA analysis preliminary confirmed that GbERF10 and GbERF17 specifically bound with ERF-binding elements in GbDXR promoter sequence. The AP2/ERF transcription factors belong to one of the largest transcription factor families in G. biloba, and their participation in the synthesis and metabolism of terpenoids have been reported in Artemisia annua (Yu et al., 2012) and Salvia miltiorrhiza (Sun et al., 2019).

The expression of GbDXR and the TTLs content have tissue variability in G. biloba. The GbDXR could expressed in all tested tissues and the highest transcript level was detected in roots, the similar expression patterns have already been reported in researching of GbLPS, GbIDS and GbMVD, the genes that are committed to the synthesize of TTLs in MEP pathway (Liao et al., 2016). Actually, the roots contain more TTLs than other tissues in our research. These results further proved that the roots are the preferential sites for the TTLs biosynthesis. The total terpenoids content in the leaves and flowers are relative higher than stems and fruits, and the ginkgo leaves are raw materials for extracting total terpenoids and flavonoids in pharmaceutical industry. Statistics analysis results showed that there is a positive relationship between the expression of GbDXR and the TTLs content, therefore, we proposed that the GbDXR plays a key role in total terpenoids metabolism.

Conclusions

TTLs are the active ingredients in G. biloba, their content in ginkgo leaves is low and will be affected by environmental conditions. The DXR gene catalyzes the first committed step specific for IPP production of the MEP pathway since to produce the precursors of TTLs biosynthesis in G. biloba. Therefore, the regulation of the expression of GbDXR gene is very important for improving the content of TTLs. Studies on gene promoters’ regulation function lay the foundation for in-depth studies of the molecular mechanism underlying TTLs biosynthesis and for the metabolic engineering of bioactive ingredients in G. biloba.

Authors’ Contributions

Conceptualization: HY, HC and SC; Funding acquisition: HC and SC; Methodology: HC, LL, LL and HY; Supervision: SC; Writing-original draft: HY, LL and LL; and Writing-review and editing: SC, HC, LL and LL. All authors read and approved the final manuscript.
Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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