

## Article

# Genomic Genome cytosine methylation is associated with may affect the variation in growth and wood property traits in populations of *Populus tomentosa*

Kaifeng Ma<sup>1,2,3</sup>, Yuepeng Song<sup>1,2</sup>, Dong Ci<sup>1,2</sup>, Daling Zhou<sup>1,2</sup>, Min Tian<sup>1,2</sup>, Deqiang Zhang<sup>1,2,3,4\*</sup>

<sup>1</sup>National Engineering Laboratory for Tree Breeding, Beijing Forestry University, Beijing 100083, China; makaifeng@bjfu.edu.cn (K.F.M.); yuepengsong@bjfu.edu.cn (Y.P.S.); cdsanx@163.com (D.C.); zag08108042@163.com (D.L.Z); minna\_tian@163.com (M.T.)

<sup>2</sup>Key Laboratory of Genetics and Breeding in Forest Trees and Ornamental Plants, Ministry of Education, College of Biological Sciences and Technology, Beijing Forestry University, Beijing 100083, China

<sup>3</sup>Beijing Key Laboratory of Ornamental Plants Germplasm Innovation & Molecular Breeding, National Engineering Research Center for Floriculture, Beijing Forestry University, Beijing 100083, China

<sup>4</sup>Xining Forestry Science Research Institute, Xining City, Qinghai Province, 810003, China

\*Correspondence: DeqiangZhang@bjfu.edu.cn; Tel.: +86-10-6233-6007

Received: date; Accepted: date; Published: date

**Abstract:** Growth and wood formation are crucial and complex biological processes during tree development. These biological regulatory processes are presumed to be controlled by DNA methylation. However, there is little direct evidence to show that genes taking part in wood regulation pathways are affected by cytosine methylation, resulting in phenotypic variations. Here, we detected epimarkers using a methylation-sensitive amplification polymorphism (MSAP) method and performed epimarker–trait association analysis on basis of nine growth and wood property traits within populations of 432 genotypes of *Populus tomentosa*. Tree height was positively correlated with relative full-methylation level, and 1,101 out of 2,393 polymorphic epimarkers were associated with phenotypic traits, explaining 1.1%–7.8% of the phenotypic variation. In total, 116 epimarkers were successfully sequenced, and 96 out of these sequences were linked to known functional putative genes. Among them, 13 candidate genes were randomly selected for verification using qRT-PCR, which and it also showed the expression of nine putative genes with important biological functions (of *PtCYP450*, *PtCpm60*, *PtPME*, *PtSCP*, *PtGH*, *PtMYB*, *PtWRKY*, *PtSTP*, and *PtABC*) that were negatively regulated by correlated with DNA methylation level. Therefore, it is suggested that changes in DNA methylation might contribute to regulating tree growth and wood property traits formation pathways.

**Keywords:** growth trait; wood property; cytosine methylation; epimarker; candidate gene; gene expression

## 1. Introduction

In plant species, Phenotypic phenotypic plasticity in plant species is a phenomenon that one genotype displays alternative phenotypes induced by epigenetic variation and changing environments and epigenetic variation [1–34], is epigenetic in that one genotype displays alternative phenotypes under different conditions [2,4]. Epigenetic regulation is not based on

alterations in DNA sequence [5-6]; rather, it gives rise to ‘epialleles’, meaning alleles with identical DNA sequences yet diverse levels of gene expression resulting from differences in their epigenetic status [7-8]. Research shows that epigenetic changes are potentially reversible, often exist in metastable states [9-10], and can be passed from one generation to the next via mitosis or meiosis [11-12]. This inherited characteristic provides an opportunity to plot epigenetic linkage maps and perform intraspecific association analysis between epigenetic alleles and traits [13-17].

Cytosine methylation, primarily the addition of a methyl group to the C5 position of a cytosine residue, is one of the best known epigenetic modifications [18]. The modification participates in various important biological responses, e.g., repressing the expression of transposons and repetitive elements, responding to biotic/abiotic stress, and taking part in early embryogenesis, stem cell differentiation, X chromosome inactivation, and genomic imprinting [19-23]. Differences in the extent of DNA methylation can give rise to varied gene expression patterns, leading to phenotypic variation [24]; furthermore, specific sites showing different patterns of 5mC (either hypermethylation or demethylation) between different individuals or tissues can affect genetic transcription, resulting in morphological changes [25-28].

For some time, researchers focused attention on selected methylated genes and their function in individual plants, such as *Arabidopsis* SUPERMAN genes with cytosine methylation affecting flower development [29], PHOSPHORIBOSYLANTHRANILATE ISOMERASE (PAI) genes supply insufficient PAI activity with cytosine methylation [30], DEMETER genes imprint MEDEA Polycomb gene by excising 5-methylcytosine [31], and FLOWERING WAGENINGEN (FWA) transcription factor gene silenced by DNA methylation in vegetative tissue but it is demethylated in the central cell of the female ovule [13,32]. In recent years, epimarkers were developed to explore epigenetic diversity and structure, and associated genes, on the basis of epialleles that can be detected using methylation-sensitive amplified polymorphism (MSAP) method in hybrids and wild populations [16,33-34]. Furthermore, these methods led to the notion that germplasm resources carrying epimutations associated with beneficial traits could be selected from plant populations [15-16].

Chinese white poplar (*Populus tomentosa* Carr.,  $2n=2x=38$ ), a native tree species with  $2n=2x=38$  chromosomes (diploid:  $n$  and  $x$  represent chromosome numbers of gametophyte and haploid, respectively) and widely distributed in the Yellow River basin, plays an important role in ecological and environmental protection. The tree has also been cultivated for commercial timber production and pulpwood because of its low contents of fermentation-inhibiting extractives, as well as high biomass conversion efficiency [35-37]. It has also been used as a model species for perennial woody plants in physiological and biochemical research, genetic diversity and structure analysis, and investigation of functional genes that participate in lignocellulose biosynthesis and growth processes [38]. Previously, we have explored the genetic/epigenetic diversity and structure of *P. tomentosa* and performed marker-trait association analysis [39-40], as well as showing that candidate wood-related genes with unique methylation patterns play critical roles in xylem biosynthesis [41]. However, epimarker-trait association analysis and seeking functional genes regulated by methylation status have not yet been performed in natural populations of *P. tomentosa*. Therefore, here we investigate the relationship between global DNA cytosine methylation markers (using MSAP) and variations in tree growth parameters and wood property parameters in order to elucidate the possible epigenetic regulation of xylem formation.

## 2. Materials and Methods

### 2.1. Plant Materials

带格式的: 字体: Palatino Linotype, 10 磅, 不对齐到网格

带格式的: 字体: (中文) +中文正文, (中文) 中文(中国)

带格式的: 字体: (中文) Times New Roman, 倾斜

带格式的: 字体: (中文) Times New Roman, 倾斜

带格式的: 字体: 倾斜

带格式的: 字体: 倾斜

带格式的: 字体: 倾斜

带格式的: 字体: 倾斜

Plant xylem materials were harvested from the germplasm bank of *P. tomentosa* located at Guanxian County (~~115°21'45"E, 36°30'54"N, 115°21'45"E~~), Shandong Province, China. The germplasm bank, including 1,047 genotypes collected from the region of China in which the species is naturally distributed, was constructed between 1982 and 1984 using root segment propagation techniques [42]. Each genotype was planted with at least three replicates with row spacing 4 m and plant spacing 4 m. In the present study, 432 unrelated genotypes (~~each genotype has with~~ three clones) originating from Beijing (20), Hebei (114), Shandong (19), Henan (114), Shaanxi (64), Shanxi (80), Gansu (6), Anhui (10), and Jiangsu (5) were selected randomly for phenotype measurements and genotyping. To deal with each of the 1,296 trees, we first stripped off the bark (approximately 5 cm × 5 cm) at breast height and cut out xylem samples with a sharp blade; ~~each of the xylem samples was divided into two parts equally, one part of the xylem material was frozen rapidly in liquid nitrogen for nucleic acid extraction and we froze part of the xylem materials rapidly in liquid nitrogen for nucleic acid extraction, and stored~~ the other part of the xylem materials was stored in plastic bags for wood property determination at normal temperature status, respectively.

## 2.2. Phenotypic Data Collection

Phenotypic data, including growth traits and wood properties, were collected and then used in statistical analysis. The growth phenotype traits of tree height (H) and diameter at breast height (DBH) were measured by using the enclosed ruler method and hypsometer, respectively. The volume of timber (V) was estimated according to the following equation [443]:  $V = \pi \times (DBH/2)^2 \times H \times f$ , and it was defined that  $f = 0.488$ .

The xylem materials that were stored in plastic bags were taken back to the laboratory and dried naturally for determining wood properties, including fiber length, fiber width, microfibril angle (MFA), and contents of lignin, holocellulose, and  $\alpha$ -cellulose. Firstly, the MFA was measured using an X-ray diffractometer (PanalyticalX'Pert Pro, Philips, Eindhoven, Netherlands) with the angle between the incident ray and the receiving optical path set to 22.4°. The main parameter settings were: tube voltage 40 kV; tube current 40 mA; scanning step 0.5° and angle of rotation 0–360°. The MFA was calculated using the method of 0.6T [424–453]. Secondly, we cut a small amount of each xylem sample into small pieces then macerated the tissue in a solution of hydrogen peroxide (30%) and glacial acetic acid (1:1, v/v) at 70°C for 48 h. For fiber length and fiber width determination, the fibrous material was washed with deionized water, processed with safranin staining, and placed uniformly over a slide, then measured using a computer image analysis system with a color television video camera (VM-60N, Olympus, Japan) according to Hart et al. [446]. Then, the xylem samples were ground into fine powder and passed through a 40–60 mesh screen; later, the contents of lignin, holocellulose, and  $\alpha$ -cellulose were determined and measured using wet chemistry analysis techniques described by Porth et al. [4547]. At the same time, near-infrared reflectance (NIR) spectroscopy was used to detect the NIR absorption spectra of the powder samples, and calibration models were developed to predict the contents of holocellulose,  $\alpha$ -cellulose, and lignin [4648].

~~The plain vanilla ANOVA (analysis of variance) was used to see the significant difference ( $P < 0.05$ ) in the phenotypic variables among the nine populations. And we used Duncan's multiple range test to detect the significance difference ( $P < 0.05$ ) within the pairs of means of each phenotypic parameter for the populations [49].~~

## 2.3. Genotyping by Methylation-Sensitive Amplified Polymorphism

The frozen xylem materials were ground into fine powder in porcelain mortars with liquid nitrogen for the extraction of nucleic acid DNA and RNA. Half of each powder sample was used for DNA isolation by the CTAB method [4750], and DNA was quantified using a NanoVue UV/visible spectrophotometer (GE Healthcare Company). We processed the DNA

带格式的: 字体: (默认) Palatino Linotype, (中文) Times New Roman, 10 磅, 不对齐到网格

带格式的: 字体: Palatino Linotype, 10 磅, 倾斜, 不对齐到网格

带格式的: 字体: Palatino Linotype, 10 磅, 不对齐到网格

带格式的: 字体: Palatino Linotype, 10 磅, 倾斜, 不对齐到网格

带格式的: 字体: (中文) + 中文正文, (中文) 中文(中国)

for methylation-sensitive amplified polymorphism (MSAP) detection, including double digestion, ligation, pre- and selective amplification, and capillary electrophoresis with fluorescence detection, as described by Ma et al. [3940]. Each DNA sample was digested separately by restriction endonuclease combinations of *EcoRI-HpaII* and *EcoRI-MspI*, and the electrophoresis results for the digested mixtures were analyzed using GeneMarker V1.7.1: four patterns of genotyping were generated (denoted '1,1'; '1,0'; '0,1'; and '0,0') according to the presence ('1') or absence ('0') of the relevant fragment in the electrophoresis lanes of the final amplification products pre-digested by *EcoRI-HpaII* and *EcoRI-MspI*, respectively.

#### 2.4. Linear Correlation Analysis and Association Analysis

Four patterns of genotyping were generated from the procedure for MSAP detection, and the percentage of each pattern relative to the total number of bands was defined as relative hemi-methylation ('1,0'), full-methylation ('0,1'), non-methylation ('1,1'), or uninformative site ('0,0'). The total relative methylation level was defined as the sum of hemi-methylation and full-methylation percentages. Linear, Pearson correlation analysis was carried out between relative methylation levels and traits (tree height, diameter at breast height, volume of timber, fiber length, fiber width, MFA, and contents of lignin, holocellulose, and  $\alpha$ -cellulose) to investigate the relationship between methylation and phenotype. Meanwhile, the relationship between gene expression level and DNA methylation level was also estimated by using linear correlation analysis. P-rimary percentage data were transformed as  $x_{ij} = \arcsin \sqrt{x_{ij}}$  before calculation ( $x_{ij}$  is the  $j$  observed value in the  $i$  group).

In order to identify correlations between phenotypic traits and the MSAP markers with four patterns at an epigenetic locus, single marker association analysis was carried out using single-factor ANOVA with a significance threshold of  $P=0.05$  or  $P=0.01$  in general. The contribution to trait variation of each MSAP marker was evaluated as the percentage of the square deviation among groups and population variance [3839]. The structural network of associated epimarkers and the traits was constructed using a Cytoscape V3.5.1 software ([https://cytoscape.org/what\\_is\\_cytoscape.html](https://cytoscape.org/what_is_cytoscape.html)) according to the instructions.

#### 2.5. Candidate Gene Screening and Gene Expression

The associated MSAP markers were separated from the selective amplification products using electrophoresis on 6% denaturing polyacrylamide gels and detected with silver staining [4851]. Then the candidate marker fragments were extracted from the gels with the Wizard SV and PCR Clean-Up System (Promega, Madison, USA), and the short PCR fragments were sequenced by Biomed Company (Beijing, China) after transformation and cloning processes [38]. Sequence homology analysis and function prediction were performed using web databases including NCBI (<https://www.ncbi.nlm.nih.gov/>) and JGI (<https://phytozome.jgi.doe.gov/pz/portal.html>).

We performed total RNA isolation using the RNeasy plant mini kit (Qiagen, Shanghai, China) from powdered xylem (mentioned in 2.3 Section), and used the first-strand cDNA (synthesized using Reverse Transcription System, Promega) for quantitative real-time PCR (qRT-PCR) processes following the description by Song et al. and Ma et al. [4952-53-50]. Primers were designed according to the functional annotation of the linked genes obtained from the homology sequence alignment. The specificity of each primer set was checked by sequencing the PCR products, and 13 candidate genes were selected for verification using *PtACTIN* as the internal control gene [5454]. Primers for qRT-PCR were designed using Primer Express 3.0 software (Applied Biosystems) and were listed in Supplementary Table 1. All reactions were performed in triplicate as technical and biological repetitions in 45 genotypes (135 trees or clones).

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格, 字体颜色: 自动设置, 不对齐到网格

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 下标, 不  
对文到网格

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格

带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格

域代码已更改

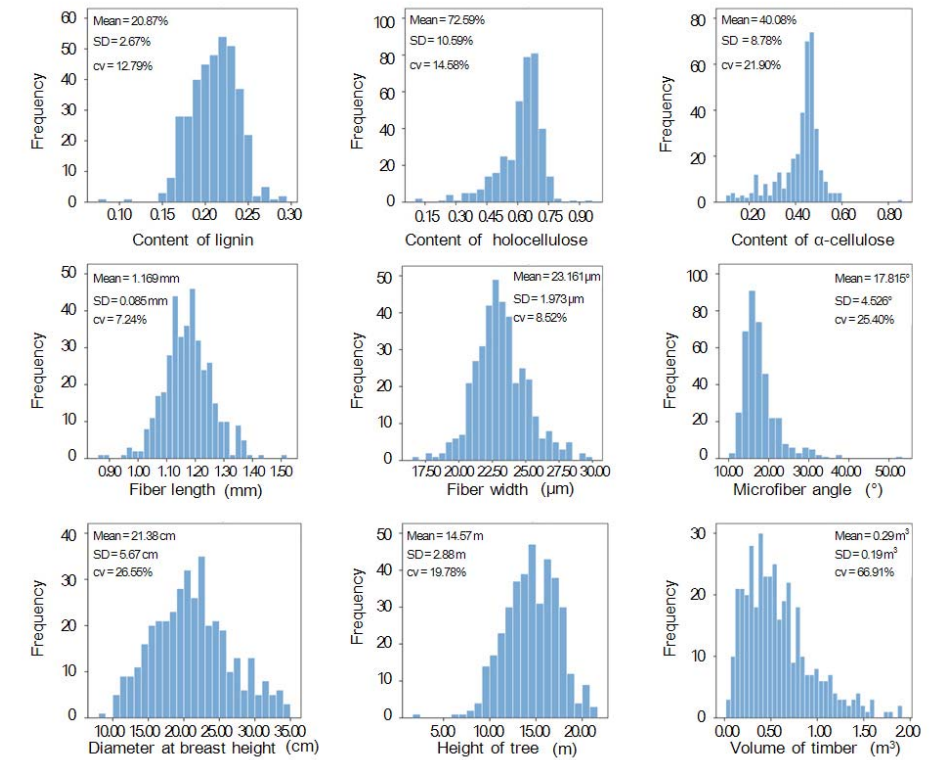
带格式的: 字体: Palatino  
Linotype, 10 磅, 倾斜, 不对齐  
到网格, 字体颜色: 自动设置, 不对齐到网格

带格式的: 字体: (中文) +中文正文,  
(中文) 中文(中国)

3. Results

3.1. Variation in Growth and Wood Characteristics

The tree phenotype, including growth traits (diameter at breast height, height of tree and volume of timber) and wood characteristics (fiber length, fiber width, microfibril angle and contents of lignin, holocellulose, and  $\alpha$ -cellulose) were quantified in natural populations planted in the germplasm bank in Guanxian County. In total, the phenotypic variation was analyzed in 432 genotypes (1,296 clones) collected from nine different geographic provenances: it was considered that this range of genotypes should provide substantial materials for selective breeding and genetic improvement. The contents of lignin, holocellulose, and  $\alpha$ -cellulose were  $20.87 \pm 2.67\%$  (mean  $\pm$  SD; SD, standard deviation),  $72.59 \pm 10.59\%$ , and  $40.08 \pm 8.78\%$ , respectively. The values of fiber length and width were distributed within the range  $0.866\text{ mm}$ – $1.512\text{ mm}$  and  $16.984\text{ }\mu\text{m}$ – $29.850\text{ }\mu\text{m}$  with mean values  $1.169 \pm 0.085\text{ mm}$  and  $23.161 \pm 1.973\text{ }\mu\text{m}$ , respectively. The mean microfibril angle was  $17.815 \pm 4.526^\circ$  ~~and displayed great genetic variation (cv = 25.40%)~~. The commercially important parameters of diameter at breast height ( $21.38 \pm 5.67\text{ cm}$ ), height of tree ( $14.57 \pm 2.88\text{ m}$ ), and volume of timber ( $0.29 \pm 0.19\text{ m}^3$ ) were also measured: ~~the stem volume demonstrated great genetic variability (cv = 66.91%). A Kolmogorov Smirnov test showed that the frequency of each quantitative trait was approximately normally distributed (Figure 1).~~



**Figure 1.** Frequency distribution and descriptive statistics for phenotypic traits among 432 genotypes of *Populus tomentosa*. The normal distribution was tested using a Kolmogorov–Smirnov test ( $P < 0.05$ ). SD, standard deviation; cv, coefficient of variation.

带格式的: 字体: (中文) +中文正文, (中文) 中文(中国)

带格式的: 字体: (默认) Palatino Linotype, (中文) Times New Roman, 10 磅, 无下划线, 不对齐到网格

带格式的: 字体: Palatino Linotype, 10 磅, 无下划线, 字体颜色: 自动设置, 不对齐到网格

带格式的: 无下划线, 字体颜色: 黑色

We performed one-way ANOVA to investigate the genetic variation in the growth and wood property traits among the nine natural populations (Figure 12). Three parameters of wood property (contents of holocellulose and  $\alpha$ -cellulose, and fiber width) showed significant differences among the populations; similarly, the growth traits of diameter at breast height, height of tree, and volume of timber displayed statistically significant significances ( $P < 0.05$ ). ~~The populations from Beijing and Jiangsu showed the lowest and highest mean values for the growth traits, respectively, according to the Duncan's multiple range test.~~



带格式的: 字体: (中文) +中文正文, (中文) 中文(中国)

**Figure 12.** Differences in phenotypic traits among nine natural populations of *Populus tomentosa*. The x- and y-axes indicate provenance and phenotypic value, respectively. Mean  $\pm$  SD (standard deviation); different letters above the bars (SD) indicate significant differences ( $P < 0.05$ ) according to Duncan's multiple range test.  ~~$P < 0.05$~~  (within each sub-graph, it shows significant difference between each two means if the pair of data sets have none common letter above the bars).

带格式的: 字体: Palatino Linotype, 小五, 无下划线, 字体颜色: 黑色

### 3.2. Linear Correlation between Phenotype and DNA Methylation levels

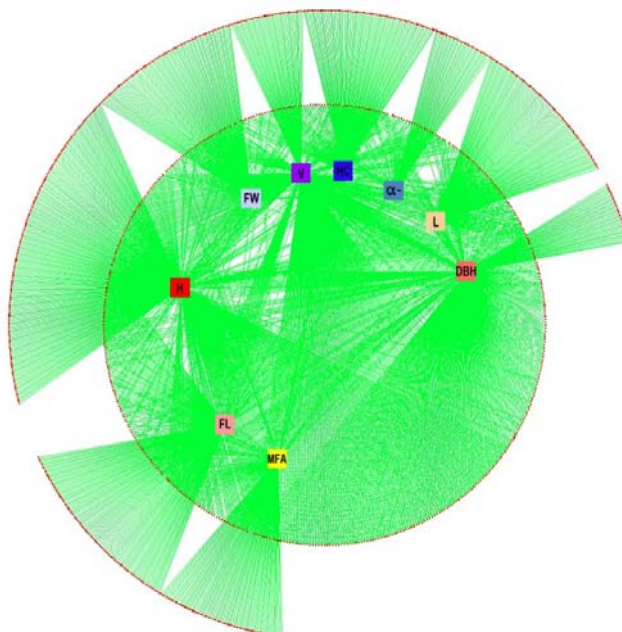
Linear correlation analysis was performed to determine trait–trait phenotypic correlations and trait–methylation level correlations among *P. tomentosa* genotypes (Table 1). Lignin content was negatively correlated with cellulose (holocellulose,  $\alpha$ -cellulose) content. Three wood and growth parameters (fiber length, timber volume, diameter at breast height) were significantly correlated with the other traits. For instance, fiber length was positively correlated with fiber width, diameter at breast height, tree height and timber volume; in contrast, fiber length was negatively correlated with microfibril angle ( $P < P < 0.01$ ). Timber volume was positively correlated with lignin content, diameter at breast height, as well as tree height, but was negatively correlated with  $\alpha$ -cellulose content ( $P < P < 0.01$ ). These results suggested that it ~~is~~ was possible to select individuals for long fibers and large quantities of stem volume according to measurements of diameter at breast height and tree height.

We also analyzed the relationships between phenotypic traits and relative gene methylation levels estimated from 2,393 polymorphic MSAP markers (epimarkers) out of 2,408 bands according to our previous data files [3940]. The relative total methylation and non-methylation levels were 26.55% and 42.71%, respectively; the relative hemi-methylation level (13.47%) was larger than that of full-methylation (13.10%) ( $P < 0.001$ ) [3940]. Here, it showed And Tree tree height was significantly negatively correlated with relative non-methylation level but positively correlated with relative full-methylation level ( $P < 0.05$ ). This calculation seemed that tree height showed a similar tendency to gene full methylation level (Table 1).

带格式的: 字体: (中文) +中文正文, (中文) 中文(中国)

### 3.3. MSAP Markers Associated with Phenotypic Traits within the Populations

Though we investigated the linear correlations between phenotypic traits and relative gene methylation levels, the relationship was unclear between traits and each of the polymorphic epimarker. On basis of the single marker ANOVA, we considered that 1,101 (630 trait-specific and 471 multi-function epimarkers) out of 2,393 polymorphic MSAP markers were associated with the nine phenotypic traits ( $P < 0.05$ ). We constructed structural networks (Figure 32) to illustrate their relationships and they showed that 125 (77 trait-specific), 127 (66 trait-specific), and 72 (30 trait-specific) epimarkers, explaining 1.19% ( $P = 0.034$ ) to 4.69% ( $P < 0.001$ ) of variation, were associated with contents of lignin, holocellulose, and  $\alpha$ -cellulose, respectively (Supplementary Table 2). Similarly, 1.06% ( $P = 0.043$ ) to 7.15% ( $P < 0.001$ ) of variation in fiber length, fiber width and microfibril angle was explained by 190 (91 trait-specific), 134 (75 trait-specific), and 140 (64 trait-specific) associated epimarkers, respectively. Finally, 312 (281 trait-specific), 414 (254 trait-specific) and 345 (309 trait-specific) epimarkers were associated with diameter at breast height, height of tree, volume of timber, respectively, explaining 1.13% ( $P = 0.035$ ) to 7.78% ( $P < 0.001$ ) of variation in those traits (Figure 32, Supplementary Table 2). The analysis suggested that these epimarkers might be associated with important functions in the regulation of complex quantitative traits, including wood property and tree growth.



**Figure 32.** Relationships between all of the significant associated epimarkers and phenotypic traits, as represented by a structural network. The square nodes in the innermost circle represent fiber length (FL), fiber width (FW), microfibril angle (MFA), diameter at breast height (DBH), height of tree (H), volume of timber (V), and contents of lignin (L), holocellulose (HC) and  $\alpha$ -cellulose ( $\alpha$ -). Nodes with red color around the central circle represent multi-function associated epimarkers. Nodes with red color around the outermost circle represent trait-specific associated epimarkers. The green lines connecting traits with epimarkers represent the phenotype variants explained by the associated epimarkers ( $p < 0.05$ ).

### 3.4. Sequencing and Functional Prediction by Homology Alignment

In order to investigate the function of genes linked with candidate epimarkers, the epimarkers that were sequenced by means of denaturing polyacrylamide gel electrophoresis and silver staining, recovery from the gels, transformation and cloning processes. In total, out of 180 randomly selected MSAP markers, we successfully sequenced 116 epimarker fragments (NCBI, Nos. MN757649–MN757764; Data S1). We aligned the sequences to the reference genome of *P. trichocarpa* and identified 96 markers that were linked to putative functional genes. The linked genes were predicted to take part in, e.g., encoding cytochrome P450 family proteins (MSAP-602), regulatory MYB and WRKY transcription factor families (MSAP-1222, MSAP-2105), ATPase activity regulation (MSAP-803, MSAP-811), regulating transmembrane transport (MSAP-1250), and glycosyl hydrolase family 1 protein (MSAP-2313), as well as other important functions (Supplementary Table3). The evidence indicated that the genes linked to epimarkers were essential for plant development, gene regulation via transcription factors, and energy metabolism in *P. tomentosa*.

### 3.5. Quantitative Expression of Candidate Genes

To examine whether the expression of putative genes was influenced by DNA methylation, we investigated the relationship between different patterns of gene expression and the relative DNA methylation levels. Thirteen candidate genes were randomly selected for verification using qRT-PCR within 45 genotypes of *P. tomentosa*: we found that the genes of *Potri.002G228400*, *Potri.010G254400*, and *Potri.018G070900* were expressed at high levels (Figure 34a). We then observed that the genes of *Potri.001G223800*, *Potri.002G228400*, *Potri.004G133800*, *Potri.005G091700*, and *Potri.018G070900* were expressed at high levels and showed relatively high non-methylation levels (Figure 34b, in red); however, the genes *Potri.001G223800*, *Potri.005G091700*, and *Potri.018G070900* were expressed at lower levels and showed relatively high hemi-methylation, full-methylation, and total-methylation levels, respectively. Negative correlations were also detected between some of the other genes and DNA methylation levels in different patterns (Figure 43b, Supplementary Table 4). Homology analysis showed that the nine correlated these epimarkers were linked with the putative genes were —*PtCYTOCHROME P450* (*PtCYP450*, *Potri.018G070900*), *PtCHAPERONES* (*PtCpn60*, *Potri.004G133800*), *PtPECTINMETHYLESTERASE* (*PtPME*, *Potri.015G127500*), *PtSERINECARBOXYPEPTIDASE* (*PtSCP*, *Potri.005G091700*), *PtGLYCOSIDE HYDROLASE* (*PtGH*, *Potri.001G223800*), *PtMYB* (*Potri.015G075800*), *PtWRKY* (*Potri.002G228400*), *PtSUGAR TRANSPORT PROTEIN* (*PtSTP*, *Potri.002G096000*), and *PtATP-BINDING CASSETTE TRANSPORTER* (*PtABC*, *Potri.010G254400*) (Supplementary Table 3).

On basis of previous research, the *Arabidopsis* CYP450 Reductase 2 (ATR2), providing electrons from NADPH to a large number of CYP450 [55], appears to be induced during lignin biosynthesis and under stress [56]. Cpn60 are large double-ring assemblies that assist in folding of the key proteins in plant growth and development [57–59]. The roles of PME have not been fully elucidated; however, this enzyme may be involved in cell elongation by modifying cell wall pectin [60]. It has long been proposed that PMEs have roles in growth

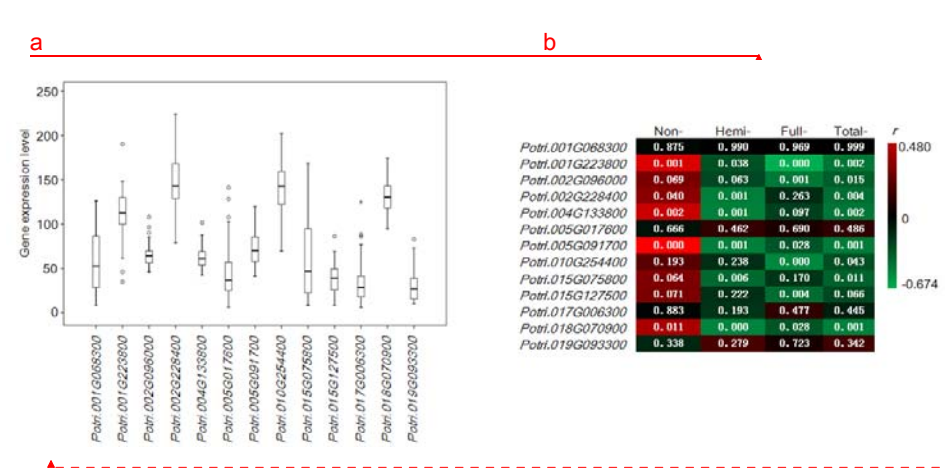
带格式的：无下划线，非突出显示

带格式的：无下划线，非突出显示

regulation, including stem growth [61–62], and *PttPME1* was demonstrated involving in mechanisms determining fiber width and length in the wood cells of aspen trees [63]. The SCP family, also called SCP-like (SCPL) family, plays a key part in plant growth, development and stress responses. Transgenic plants of *Nicotiana tabacum* over-expressing *NtSCP1* show reduced cell elongation [64]. In *Triticum aestivum*, SCP regulates cell death during vascular tissue development [65]. GH proteins are broadly distributed in organisms and  $\beta$ -glucosidases belonging to GH family 1 have been implicated in several fundamental processes, including lignification [66–67].

MYB and WRKY are two transcription factor families involved in most biological processes. It was shown that the MYB61, regulated by NAC29/31, binds with *CELLULOSE SYNTHASE (CESAs)*, which in turn activates gene expression in secondary wall cellulose synthesis in *Oryzasativa* [68]. Similarly, *PtrMYB152* is over-expressed in secondary wall-forming cells, resulting in specific activation of lignin biosynthetic genes in *P. trichocarpa* [69]. It was also reported that *PtrWRKY19* and *VvWRKY2* may function as regulators of pith secondary wall formation in poplar and lignification in grapevine, respectively [70–71].

STPs and ABC transporters are important for transmembrane transport, an essential biological process in cells. STPs are high-affinity hexose transporters with sink-specific tissue expression [72–74]; constitutive over-expression of *STP13* resulted in seedlings with increased biomass when grown on media supplemented with sugar [75]. It was suggested that *MeSTPs* may play a role in early tuber growth, the period when these genes were mainly expressed in *Manihot esculenta* [76]. A breakthrough study demonstrated that a transporter of the ABC family pumps the monolignol p-coumaryl alcohol, one of the three main monolignols synthesized in the cytosol, across the plasma membrane [77–78]. It was also reported that the stem vascular morphology was slightly disorganized in *abcb14-1* mutants, with decreased phloem area in the vascular bundle and decreased xylem vessel lumen diameter [79]. Therefore, it seemed that cytosine methylation might take part in regulating expression of the putative genes and affect the growth and wood property traits.



**Figure 43.** Expression levels of candidate genes and their correlations with relative DNA methylation levels. (a) Gene expression level determined by quantitative real-time polymerase chain reaction (qRT-PCR). The x- and y-axes indicate, respectively, gene name and expression level relative to *PtACTIN*. (b) Linear correlations between gene expression levels and relative

带格式的: 无下划线, 非突出显示

带格式的: 无下划线

带格式的: 无下划线, 字体颜色: 文字 1

带格式的: 字体: Palatino Linotype, 10 磅, 无下划线, 不对齐到网格

带格式的: 字体: Palatino Linotype, 10 磅, 无下划线, 不对齐到网格

带格式的: 字体: (默认) Arial Unicode MS, (中文) Arial Unicode MS, 五号, (中文) 中文(中国)

带格式的: 字体: (默认) Palatino Linotype, (中文) +中文正文, 10 磅, 无下划线, 字体颜色: 自动设置

带格式的: 字体: (中文) +中文正文, (中文) 中文(中国)

DNA methylation levels. Non-, Hemi-, Full-, and Total- indicate relative non-methylation, hemi-methylation, full-methylation, and total-methylation levels, respectively, estimated by Pearson correlation coefficient ( $r$ , red-black-green color scale from positive to negative correlation). And the white numbers ( $P$ -value) in each cell indicates the significance of difference.

#### 4. Discussion

Growth traits and wood properties, determining the business value and potential for energy production, are the most important phenotypes for commercial timber—which is the most important renewable bioenergy source in nature. *P. tomentosa* is a native species mainly used for timber in vast regions of North China, thus, it is imperative to investigate the mechanisms of growth regulation and wood formation to underpin selection of germplasm resources and breeding for genetic improvement. In this paper, we measured and calculated values of nine parameters of phenotypic traits (diameter at breast height, height of tree, and volume of timber; content of lignin, content of holocellulose, content of  $\alpha$ -cellulose, fiber length, fiber width, and microfibril angle) among 1,296 plants (432 genotypes) from natural tree populations. Then we explored the relationships between those traits and variation in DNA methylation detected using MSAP and qRT-PCR methods.

##### 4.1. Relative Full-methylation Was Positively Correlated with Tree Height

On basis of the statistics of the different genotypes, we found the coefficient of variation in traits was 7.24%–66.91%, and the growth and wood property traits showed significant variation among the nine natural populations, with the exception of lignin content, fiber length and microfibril angle. This phenotypic variation, or plasticity, might correlate with genome DNA methylation, the level of which plays an important role in genome stabilization and transposable element repression [19,22,18,21]. Previous evidence showed that the methylation level is correlated with phenotype [80]. For instance, negative correlation was detected between genomic methylation level and gene expression in maize; similarly, negative correlations were reported between methylation level and energy use efficiency and crop yield in *Brassica napus* [52,53,80–81]. However, in the woody ornamental plant *Meimeij*, the leaf length, width, and area were positively correlated with relative full and total methylation levels [46,17]. In hybrids of poplar, a positive correlation was demonstrated between DNA methylation percentage and productivity [54,82]. We previously showed that the net photosynthetic rate, tree height and diameter at breast height were positively correlated with relative total methylation and hemi-methylation levels in an intraspecific hybrid population of *P. tomentosa* [38,39]; here we found the similar result among the natural populations, that relative full-methylation level was positively correlated with tree height.

##### 4.2. DNA Methylation Negatively Regulates Putative Genes Participating in Growth and Wood Formation

Previous studies have showed that methylation is essential for gene exploration and epimarker-assisted analysis in plant populations [44,15,17,6,34,3]. For instance, Long et al. [14] constructed a new linkage epi map with both epimarkers and markers in *Brassica napus*, and identified 125 additional significant quantitative trait loci associated with seven important agronomic traits. *PtHT1.1*, *PtHT1.2*, *PtPsbK*, *PtPIN1.2*, *PtMYB60*, and *PtMYB61* were found to be modified by DNA methylation and regarded as playing roles in leaf formation and regulation of photosynthesis in *P. simonii* [33,34]. In our research, we detected 1,101 epimarkers associated with growth and wood property traits. From these we identified 96 epimarker-linked putative genes with known functions, 13 of which were randomly selected for qRT-PCR analysis. We found that putative genes and it was found *PtCYP450*, *PtCpn60*,

带格式的: 无下划线, 突出显示

*PtPME*, *PtSCP*, *PtGH*, *PtMYB*, *PtWRKY*, *PtSTP*, and *PtABC*, the functions of which are discussed below, were negatively correlated with relative regulated by DNA methylation level. Meanwhile, it was demonstrated *PtPME1* involved in mechanisms determining fiber width and length in the wood cells of aspen trees [63]. Transcription factor genes *PtMYB152* is over-expressed in secondary wall-forming cells, resulting in specific activation of lignin biosynthetic genes, and *PtWRKY19* may function as regulators of pith secondary wall formation in *P. trichocarpa* [69,71]. The *ABC14-1* plays role in decreasing phloem area in the vascular bundle and xylem vessel lumen diameter in *Arabidopsis* [79].

CYP450 takes part in biological synthesis of secondary metabolites including brassinolides (BRs), plant hormones, flavonoid compounds, alkaloids, as well as intermediates of lignin biosynthesis [55–57]. The *Arabidopsis* CYP450 Reductase2 (ATR2), providing electrons from NADPH to a large number of CYP450 [58], appears to be induced during lignin biosynthesis and under stress [56]. In the *atr2* mutation, the total lignin amount in the main inflorescence stem was reduced by 6% and the cellulose was more susceptible to enzymatic hydrolysis after alkaline pretreatment [56,59]. More markedly than disrupting ATR2, disrupting *Cytochrome Isoform D (CB5D)* controlling syringyl (S) lignin biosynthesis resulted in >60% reduction in S lignin subunit levels [60].

Cpn60 are large double ring assemblies that assist in folding of the key proteins in plant growth and development [61–63]. In *A. thaliana*, chloroplast chaperonin subunit Cpn60 $\beta$ 4, forming a hetero-oligomeric Cpn60 complex with Cpn60 $\alpha$ 1 and Cpn60 $\beta$ 1– $\beta$ 3, is specifically and strictly required for the folding of the NDH subunit NdhH [62]. The *cpn60 $\alpha$ 1* mutant plant showed retarded growth and pale green leaf compared with *err27* and wild types [62]. Cpn60 $\beta$ 4 was presumed to be a key factor in plant growth, development and flowering [63].

The roles of PME have not been fully elucidated; however, this enzyme may be involved in cell elongation by modifying cell wall pectin [64]. Many studies have examined the correlations between certain phenotypes and expression of PMEs, which have long been proposed to have roles in growth regulation, including stem growth [65]. It was demonstrated that *PME35* is involved in pectin mediated strengthening of supporting tissue in the basal part of the *Arabidopsis* inflorescence stem [66], while *PtPME1* is involved in mechanisms determining fiber width and length in the wood cells of aspen trees [67].

The SCP family, also called SCP-like (SCPL) family, plays a key part in plant growth, development and stress responses. Transgenic plants of *Nicotiana tabacum* over-expressing *NtSCP1* show reduced cell elongation [68]. In wheat, *Triticum aestivum*, SCP regulates cell death during vascular tissue development [69]. In addition, *PtSCPL* genes may be involved in disease resistance in *P. trichocarpa* [70]. GH proteins are broadly distributed in organisms and  $\beta$ -glucosidases belonging to GH family 1 have been implicated in several fundamental processes, including lignification [71–72].

MYB and WRKY are two transcription factor families involved in most biological processes. It was shown that the MYB61, regulated by NAC29/31, binds with *CELLULOSE SYNTHASE (CESAs)*, which in turn activates gene expression in secondary wall cellulose synthesis in *Oryza sativa* [73]. Similarly, *PtMYB152* is over-expressed in secondary wall-forming cells, resulting in specific activation of lignin biosynthetic genes in *P. trichocarpa* [74]. It was also reported that *PtWRKY19* and *VvWRKY2* may function as regulators of pith secondary wall formation in poplar and lignification in grapevine, respectively [75–76].

STPs and ABC transporters are important for transmembrane transport, an essential biological process in cells. STPs are high affinity hexose transporters with sink specific tissue expression [77–79]; constitutive over expression of *STP13* resulted in seedlings with increased biomass when grown on media supplemented with sugar [80]. It was suggested that *MeSTP* may play a role in early tuber growth, the period when these genes were mainly expressed in *Manihot esculenta* [81]. A breakthrough study demonstrated that a transporter of

带格式的：无下划线，非突出显示

带格式的：无下划线，非突出显示

带格式的：无下划线，非突出显示

带格式的：无下划线，非突出显示

带格式的：无下划线，非突出显示

带格式的：无下划线，非突出显示

带格式的：字体：倾斜，无下划线

the ABC family pumps the monolignol p-coumaryl alcohol, one of the three main monolignols synthesized in the cytosol, across the plasma membrane [82–83]. It was also reported that the stem vascular morphology was slightly disorganized in *abcb14-1* mutants, with decreased phloem area in the vascular bundle and decreased xylem vessel lumen diameter [84].

The evidence above ~~strongly seemed suggests~~ that genes ~~with cytosine methylation modifications are~~ involved in regulating growth and wood development in *P. tomentosa* ~~might affect by cytosine methylation modifications~~. Furthermore, the individual trees were planted in the same place, and thus it could be considered that the epi-variation might be stably inherited from one generation to the next, by mitosis and/or meiosis. Therefore, along with genomic mutations, the epi-variation associated with beneficial traits could usefully be selected for breeding [85]. The epimarkers ~~that needed to be verified developed here will may also~~ provide a ~~strong basis new sight from which to develop future for~~ breeding programs in this commercially important tree ~~and potentially also in other tree species~~.

## 5. Conclusions

The quantitative traits of the growth and wood property are important for commercial timber tree species ~~which are not able to keep up with the dramatically increasing demand~~. Many biotechnology methods have been used for the investigation of genetic architecture and regulatory mechanisms underlying growth characteristics and wood formation. Recently, DNA methylation, one kind of the best studied epigenetic modifications, is introduced to investigate xylem regulation mechanism. The objective of the present study was to reveal relationship between cytosine methylation and ~~tree growth and~~ wood property traits, ~~respectively~~. It was found that the tree height was positively correlated with relative full methylation level. And 1,101 single- and multi-function MSAP markers explaining 1.1%–7.8% of phenotypic variation were associated with growth traits (diameter at breast height, height of tree and volume of timber) and wood characteristics (fiber length, fiber width, microfibril angle, lignin, holocellulose, and  $\alpha$ -cellulose). It was demonstrated that 96 sequences, out of 116 successfully sequenced epimarkers, were linked to ~~putative known functional~~ genes. ~~The expression levels of nine~~ Among them, 13 candidate genes were randomly selected for verification using qRT-PCR, which showed nine putative genes ~~with important biological functions~~ (*PtCYP450*, *PtCpn60*, *PtPME*, *PtSCP*, *PtGH*, *PtMYB*, *PtWRKY*, *PtSTP*, and *PtABC*) ~~that were negatively regulated correlated by with~~ DNA methylation. Our results implied that widespread natural variation of DNA methylation ~~might~~ contributes to regulating tree growth and wood formation ~~pathways~~. These and the findings will enhance our understanding of epigenetics in ~~tree growth and~~ xylem formation, ~~and are significant for molecular assisted selection (MAS) for woody plant improvement~~.

**Supplementary Materials:** Supplementary materials can be found at <http://www.XXX>. Table S1: Primer sequences for Real-time PCR. Table S2: MSAP markers associated with phenotypic traits and the variation explanation in natural population of *Populus tomentosa*. Table S3: Homologous alignment and gene function analysis. Table S4: The gene expression levels detected using qRT-PCR and relative cytosine methylation levels within 45 genotypes of *Populus tomentosa*. Data S1: Sequences for the 116 MSAP markers.

**Sequencing Data:** All of the sequences were submitted to NCBI (<https://www.ncbi.nlm.nih.gov/>) with accession numbers: MN757649–MN757764.

**Author Contributions:** D.Q.Z. designed the experiments. K.F.M., Y.P.S., and D.C. collected the plant materials and phenotypic data. K.F.M., D.L.Z., and M.T. did the experiment in gene cloning and quantification of gene expression. K.F.M. detected the molecular markers and analyzed all of the data profiles. K.F.M. and D.Q.Z. wrote the manuscript. Y.P.S., D.C., D.L.Z., and M.T. provided suggestions for manuscript revision.

带格式的: 字体: Palatino Linotype, 10 磅, 无下划线, 不对齐到网格, 非突出显示

带格式的: 字体: Palatino Linotype, 10 磅, 无下划线, 不对齐到网格, 非突出显示

带格式的: 字体: (中文) + 中文正文, (中文) 中文(中国), 突出显示

带格式的: 字体: Palatino Linotype, 10 磅, 倾斜, 无下划线, 不对齐到网格

**Funding:** This work was supported by the National Natural Science Foundation of China (No. 31872671).

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Labra, M.; Ghiani, A.; Citterio, S.; Sgorbati, S.; Sala, F.; Vannini, C.; Vannini, C.; Ruffini-Castiglione, M.; Bracale, M. Analysis of cytosine methylation pattern in response to water deficit in pea root tips. *Plant Biology* **2002**, *4*, 694–699.
2. Nicotra, A.B.; Atkin, O.K.; Bonser, S.P.; Davidson, A.M.; Finnegan, E.J.; Mathesius, U.; Poot, P.; Purugganan, M.D.; Richards, C.L.; Valladares, F.; et al. Plant phenotypic plasticity in a changing climate. *Trends Plant Sci.* **2010**, *15*, 684–692.
3. Niederhuth, C.E.; Bewick, A.J.; Ji, L.; Alabady, M.S.; Kim, K.D.; Li, Q.; Rohr, N.A.; Rambani, A.; Burke, J.M.; Udall, J.A.; et al. Widespread natural variation of DNA methylation within angiosperms. *Genome Biol.* **2016**, *17*, 194.
4. Richards, E.J. Natural epigenetic variation in plant species: a view from the field. *Curr. Opin. Plant Biol.* **2011**, *14*, 204–209.
5. Teixeira, F.K.; Colot, V. Repeat elements and the *Arabidopsis* DNA methylation landscape. *Heredity* **2010**, *105*, 14–23.
6. Herrera, C.M.; Bazaga, P. Epigenetic differentiation and relationship to adaptive genetic divergence in discrete populations of the violet *Viola cazorlensis*. *New Phytol.* **2010**, *187*, 867–876.
7. Rakan, V.K.; Preis, J.J.; Morgan, H.; Whitelaw, E. The marks, mechanisms and memory of epigenetic states in mammals. *Biochem. J.* **2001**, *356*, 1–10.
8. Rakan, V.K.; Blewitt, M.E.; Druker, R.; Preis, J.I.; Whitelaw, E. Metastable epialleles in mammals. *Trends Genet.* **2002**, *18*, 348–351.
9. Foerster, A.M.; Dinh, H.Q.; Sedman, L.; Wohlrab, B.; Scheid, O.M. Genetic rearrangements can modify chromatin features at epialleles. *PLoS Genet.* **2011**, *7*, e1002331.
10. Vaughn, M.W.; Tanurdžić, M.; Lippman, Z.; Jiang, H.; Carrasquillo, R.; Rabinowicz, P.D.; Dedhia, N.; McCombie, W.R.; Agier, N.; Bulski, A.; et al. Epigenetic natural variation in *Arabidopsis thaliana*. *PLoS Biol.* **2007**, *5*, 1617–1629.
11. Angers, B.; Castonguay, E.; Massicotte, R. Environmentally induced phenotypes and DNA methylation: how to deal with unpredictable conditions until the next generation and after. *Mol. Ecol.* **2010**, *19*, 1283–1295.
12. Down, R.H.; Pelizzola, M.; Schmitz, R.J.; Lister, R.; Down, J.M.; Nery, J.R.; Dixon, J.E.; Ecker, J.R. Widespread dynamic DNA methylation in response to biotic stress. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, E2183–2191.
13. Fujimoto, R.; Sasaki, T.; Kudoh, H.; Taylor, J.M.; Kakutani, T.; Dennis, E.S. Epigenetic variation in the *FWA* gene within the genus *Arabidopsis*. *Plant Journal* **2011**, *66*, 831–843.
14. Zhang, X.; Shiu, S.; Cal, A.; Borevitz, J.O. Global analysis of genetic, epigenetic and transcriptional polymorphisms in *Arabidopsis thaliana* using whole genome tiling arrays. *PLoS Genet.* **2008**, *4*, e1000032.
15. Long, Y.; Xia, W.; Li, R.; Wang, J.; Shao, M.; Feng, J.; King, G.J.; Meng, J. Epigenetic QTL mapping in *Brassica napus*. *Genetics* **2011**, *189*, 1093–1102.
16. Foust, C.; Preite, V.; Schrey, A.W.; Alvarez, M.; Robertson, M.; Verhoeven, K.J.F.; Richards, C.L. Genetic and epigenetic differences associated with environmental gradients in replicate populations of two salt marsh perennials. *Mol. Ecol.* **2016**, *25*, 1639–1652.

带格式的: 字体: (中文) +中文正文, (中文) 中文(中国)

4617. Ma, K.; Sun, L.; Cheng, T.; Pan, H.; Wang, J.; Zhang, Q. Epigenetic variance, performing cooperative structure with genetics, is associated with leaf shape traits in widely distributed populations of ornamental tree *Prunus mume*. *Front. Plant Sci.* **2018**, *9*, 41.
4718. Cervera, M.T.; Ruiz-Garcia, L.; Martinez-Zapater, J.M. Analysis of DNA methylation in *Arabidopsis thaliana* based on methylation-sensitive AFLP markers. *Mol. Genet. Genomics* **2002**, *268*, 543–552.
4819. Lisch, D. Epigenetic regulation of transposable elements in plants. *Annu. Rev. Plant Biol.* **2009**, *60*, 43–66.
4920. Hsieh, T.; Shin, J.; Uzawa, R.; Silva, P.; Cohen, S.; Bauer, M.J.; Hashimoto, M.; Kirkbride, R.C.; Harada, J.J.; Zilberman, D.; et al. Regulation of imprinted gene expression in *Arabidopsis* endosperm. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 1755–1762.
2021. Uthup, T.K.; Ravindran, M.; Bini, K.; Thakurdas, S. Divergent DNA methylation patterns associated with abiotic stress in *Hevea brasiliensis*. *Mol. Plant* **2011**, *4*, 996–1013.
2422. Diez, C.M.; Roessler, K.; Gaut, B.S. Epigenetics and plant genome evolution. *Curr. Opin. Plant Biol.* **2014**, *18*, 1–8.
2223. Rico, L.; Ogaya, R.; Barbeta, A.; Pnuelas, J. Changes in DNA methylation fingerprint of *Quercus ilex* trees in response to experimental field drought simulating projected climate change. *Plant Biology* **2014**, *16*, 419–427.
2324. Tang, X.; Tao, X.; Wang, Y.; Ma, D.; Li, D.; Yang, H.; Ma, X. Analysis of DNA methylation of perennial ryegrass under drought using the methylation-sensitive amplification polymorphism (MSAP) technique. *Mol. Genet. Genomics* **2014**, *289*, 1075–1084.
2425. Kakutani, T.; Munakata, K.; Richards, E.; Hirohiko, H. Meiotically and mitotically stable inheritance of DNA hypomethylation induced by *ddm1* mutation of *Arabidopsis thaliana*. *Genetics* **1999**, *151*, 831–838.
2526. Cubas, P.; Vincent, C.; Coen, E. An epigenetic mutation responsible for natural variation in floral symmetry. *Nature* **1999**, *401*, 157–161.
2627. Kashkush, K.; Khasdan, V. Large-scale survey of cytosine methylation of retrotransposons and the impact of read out transcription from long terminal repeat on expression of adjacent rice genes. *Genetics* **2007**, *177*, 1975–1985.
2728. Vining, K.J.; Pomraning, K.R.; Wilhelm, L.J.; Priest, H.D.; Pellegrini, M.; Mockler, T.C.; Freitag, M.; Strauss, S.H. Dynamic DNA cytosine methylation in the *Populus trichocarpa* genome: tissue-level variation and relationship to gene expression. *BMC Genomics* **2012**, *13*, 27.
2829. Jacobsen, S.E.; Meyerowitz, E.M. Hypermethylated *SUPERMAN* epigenetic alleles in *Arabidopsis*. *Science* **1997**, *277*, 1100–1103.
2930. Bender, J.; Fink, G.R. Epigenetic control of an endogenous gene family is revealed by a novel blue fluorescent mutant of *Arabidopsis*. *Cell* **1995**, *83*, 725–734.
3031. Choi, Y.; Gehring, M.; Johnson, L.; Hannon, M.; Harada, J.J.; Goldberg, R.B.; Jacobsen, S.E.; Fischer, R.L. DEMETER, a DNA glycosylase domain protein, is required for endosperm gene imprinting and seed viability in *Arabidopsis*. *Cell* **2002**, *110*, 33–42.
3432. Kinoshita, T.; Miura, A.; Choi, Y.; Kinoshita, Y.; Cao, X.; Jacobsen, S.E.; Fischer, R.L.; Kakutani, T. One-way control of FWA imprinting in *Arabidopsis* endosperm by DNA methylation. *Science* **2004**, *303*, 521–523.
3233. Schmitz, R.J.; He, Y.; Valdés-López, O.; Khan, S.M.; Joshi, T.; Urich, M.A.; Nery, J.R.; Diers, B.; Xu, D.; Stacey, G.; et al. Epigenome-wide inheritance of cytosine methylation variants in a recombinant inbred population. *Genome Res.* **2013**, *23*, 1663–1674.
3334. Ci, D.; Song, Y.; Du, Q.; Tian, M.; Han, S.; Zhang, D. Variation in genomic methylation in natural populations of *Populus simonii* is associated with leaf shape and photosynthetic traits. *J. Exp. Bot.* **2016**, *67*, 723–737.

- [3435](#). Zhu, Z. Collection, conservation and utilization of plus tree resources of *Populus tomentosa* in China. *J. Beijing For. Univ.* **1992**, *14*, 1–25.
- [3536](#). Zhu, Z.; Zhang, Z. The status and advances of genetic improvement of *Populus tomentosa* Carr. *J. Beijing For. Univ.* **1997**, *6*, 1–7.
- [3637](#). Zhang, D.; Zhang, Z.; Yang, K.; Li, B. Genetic mapping in (*Populus tomentosa* × *Populus bolleana*) and *P. tomentosa* Carr. Using AFLP markers. *Theor. Appl. Genet.* **2004**, *108*, 657–662.
- [3738](#). Du, Q.; Pan, W.; Xu, B.; Li, B.; Zhang, D. Polymorphic simple sequence repeat (SSR) loci within cellulose synthase (*PtoCesA*) genes are associated with growth and wood properties in *Populus tomentosa*. *New Phytol.* **2013**, *197*, 763–776.
- [3839](#). Ma, K.; Song, Y.; Jiang, X.; Zhang, Z.; Li, B.; Zhang, D. Photosynthetic response to genome methylation affects the growth of Chinese white poplar. *Tree Genet. Genomes* **2012**, *8*, 1407–1421.
- [3940](#). Ma, K.; Song, Y.; Yang, X.; Zhang, Z.; Zhang, D. Variation in genomic methylation in natural populations of Chinese white poplar. *PLoS ONE* **2013**, *8*, e63977.
- [4041](#). Wang, Q.; Ci, D.; Li, T.; Li, P.; Song, Y.; Chen, J.; Quan, M.; Zhou, D.; Zhang, D. The role of DNA methylation in xylogenesis in different tissues of poplar. *Front. Plant Sci.* **2016**, *7*, 1003.
- [42](#). Du, Q.; Wang, B.; Wei, Z.; Zhang, D.; Li, B. Genetic diversity and population structure of Chinese white poplar (*Populus tomentosa*) revealed by SSR markers. *J. Hered.* **2012**, *103*, 853–862.
- [4443](#). Yang, H.; Meng, X.; Cheng, J.; Zhao, L.; Wang, X. Study on estimating the volume of a single tree using normal form factor. *Forest Resources Management* **2005**, *1*, 39–41.
- [4244](#). Andersson, S.; Serimaa, R.; Torkkeli, M.; Paakkari, T.; Saranpää, P.; Pesonen, E. Microfibril angle of Norway spruce [*Picea abies* (L.) Karst.] compression wood: comparison of measuring techniques. *J. Wood Sci.* **2000**, *46*, 343–349.
- [4345](#). Wang, Y.; Liu, C.; Zhao, R.; Mccord, J.; Rials, T.G.; Wang, S. Anatomical characteristics, microfibril angle and micromechanical properties of cottonwood (*Populus deltoides*) and its hybrids. *Biomass Bioenerg.* **2016**, *93*, 72–77.
- [4446](#). Hart, J.F.; De-Araujo, F.; Thomas, B.R.; Mansfield, S.D. Wood quality and growth characterization across intra- and inter-specific hybrid aspen clones. *Forests* **2013**, *4*, 786–807.
- [4547](#). Porth, I.; Klápště, J.; Skyba, O.; Lai, B.S.K.; Geraldine, A.; Muchero, W.; Tuskan, G.A.; Douglas, C.J.; El-Kassaby, Y.A.; Mansfield, S.D. *Populus trichocarpa* cell wall chemistry and ultrastructure trait variation, genetic control and genetic correlations. *New Phytol.* **2013**, *197*, 777–790.
- [4648](#). Schimleck, L.R.; Kube, P.D.; Raymond, C.A. Genetic improvement of kraft pulp yield in *Eucalyptus nitens* using cellulose content determined by near infrared spectroscopy. *Can. J. Forest Res.* **2004**, *34*, 2363–2370.
- [49](#). Aleong, I.; Howard, D. Extensions of the Duncan's Multiple Range Test for unbalanced data. *J. Appl. Stat.* **1985**, *12*, 83–90.
- [4750](#). Murray, M.G.; Thompson, W.F. Rapid isolation of high molecular weight plant DNA. *Nucl. Acids Res.* **1980**, *8*, 4321–4325.
- [4851](#). Tixier, M.H.; Sourdille, P.; Röder, M.S.; Leroy, P.; Bernard, M. Detection of wheat microsatellites using a non-radioactive silver-nitrate staining method. *J. Genet. Breed.* **1997**, *51*, 175–177.
- [4952](#). Song, Y.; Ma, K.; Bo, W.; Zhang, Z.; Zhang, D. Sex-specific DNA methylation and gene expression in andromonoecious poplar. *Plant Cell Rep.* **2012**, *31*, 1393–1405.
- [5053](#). Ma, K.; Song, Y.; Huang, Z.; Lin, L.; Zhang, Z.; Zhang, D. The low fertility of Chinese white poplar: dynamic changes in anatomical structure, endogenous hormone

带格式的：无下划线，字体颜色：自动设置

带格式的：无下划线

带格式的：无下划线，字体颜色：自动设置

带格式的：缩进：左侧：0 厘米，首行缩进：0 字符

带格式的：无下划线

带格式的：字体：Palatino Linotype，10 磅，无下划线，字体颜色：蓝色

带格式的：字体：(中文) Times New Roman，无下划线

带格式的：字体：(中文) Times New Roman，无下划线

带格式的：字体：倾斜，无下划线

带格式的：字体：加粗，无下划线

带格式的：字体：倾斜，无下划线

带格式的：无下划线

带格式的：无下划线

concentrations, and key gene expression in the reproduction of a naturally occurring hybrid. *Plant Cell Rep.* **2013**, *32*, 401–414.

54. Zhang, D.; Du, Q.; Xu, B.; Zhang, Z.; Li, B. The actin multigene family in *Populus*: organization, expression and phylogenetic analysis. *Mol. Genet. Genomics* **2010**, *284*, 105–119.
55. Niu, G.; Zhao, S.; Wang, L.; Dong, W.; Liu, L.; He, Y. Structure of the *Arabidopsis thaliana* NADPH-cytochrome P450 reductase 2 (ATR2) provides insight into its function. *FEBS J.* **2017**, *284*, 754–765.
52. Tsaftaris, A.S.; Kafka, M.; Polidoros, A.; Tani, W. Epigenetic changes in maize DNA and heterosis. In: CIMMYT. 1997. Abst. The genetics and exploitation of heterosis in crops. Int. Symp. Mexico City 1997, 112–113.
53. Hauben, M.; Haesendonckx, B.; Standaert, E.; Kelen, K.V.D.; Azmi, A.; Akpo, H.; Breusegem, F.V.; Cuisez, Y.; Bots, M.; Lambert, B.; et al. Energy use efficiency is characterized by an epigenetic component that can be directed through artificial selection to increase yield. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 20109–20114.
54. Courcilleau, D.; Bogeat Triboulot, M.; Thiec, D.L.; Lafon-Placette, C.; Delaunay, A.; El-Soud, W.A.; Brignolas, F.; Maury, S. DNA methylation and histone acetylation: genotypic variations in hybrid poplars, impact of water deficit and relationships with productivity. *Ann. For. Sci.* **2010**, *67*, 208.
55. Kitada, C.; Cong, Z.; Tanaka, Y.; Yamazaki, M.; Saito, K. Differential expression of two cytochrome P450s involved in the biosynthesis of flavones and anthocyanins in chemo-variant forms of *Perilla frutescens*. *Plant Cell Physiol.* **2001**, *42*, 1338–1344.
56. Sundin, L.; Vanholme, R.; Geerinck, J.; Goeminne, G.; Hofer, R.; Kim, H.; Ralph, J.; Boerjan, W. Mutation of the inducible *ARABIDOPSIS THALIANA* CYTOCHROME P450 REDUCTASE2 alters lignin composition and improves saccharification. *Plant Physiol.* **2014**, *166*, 1956–1971.
57. Parage, C.; Foureau, E.; Kellner, F.; Burlat, V.; Mahroug, S.; Lanoue, A.; de Bernonville, T.D.; Londono, M.A.; Carqueijeiro, I.; Oudin, A.; et al. Class II cytochrome P450 reductase governs the biosynthesis of alkaloids. *Plant Physiol.* **2016**, *172*, 1563–1577.
58. Niu, G.; Zhao, S.; Wang, L.; Dong, W.; Liu, L.; He, Y. Structure of the *Arabidopsis thaliana* NADPH-cytochrome P450 reductase 2 (ATR2) provides insight into its function. *FEBS J.* **2017**, *284*, 754–765.
59. Gou, M.; Ran, X.; Martin, D.W.; Liu, C. The scaffold proteins of lignin biosynthetic cytochrome P450 enzymes. *Nat. Plants* **2018**, *4*, 299–310.
60. Gou, M.; Yang, X.; Zhao, Y.; Ran, X.; Song, Y.; Liu, C. Cytochrome b5 is an obligate electron shuttle protein for syringyl lignin biosynthesis in *Arabidopsis*. *Plant Cell* **2019**, *31*, 1344–1366.
61. Hill, J.E.; Hemmingsen, S.M. *Arabidopsis thaliana* type I and II chaperonins. *Cell Stress Chaperon.* **2001**, *6*, 190–200.
62. Peng, L.; Fukao, Y.; Myouga, F.; Motohashi, R.; Shinozaki, K.; Shikanai, T. A chaperonin subunit with unique structures is essential for folding of a specific substrate. *PLOS PLoS Biol.* **2011**, *9*, e1001040.
59. Tiwari, L.D.; Grover, A. Cpn60β4 protein regulates growth and developmental cycling and has bearing on flowering time in *Arabidopsis thaliana* plants. *Plant Sci.* **2019**, *286*, 78–88.
60. Micheli, F. Pectin methylesterases: cell wall enzymes with important roles in plant physiology. *Trends Plant Sci.* **2001**, *6*, 414–419.
61. Wolf, S.I.; Mouille, G.; Pelloux, J. Homogalacturonan methyl-esterification and plant development. *Mol. Plant* **2009**, *2*, 851–860.

带格式的：字体：(中文) +中文正文，(中文) 中文(中国)

带格式的：无下划线

带格式的：无下划线，字体颜色：文字 1

6662. Hongo, S.; Sato, K.; Yokoyama, R.; Nishitani, K. Demethylesterification of the primary wall by *PECTIN METHYLESTERASE35* provides mechanical support to the *Arabidopsis* stem. *Plant Cell* **2012**, *24*, 2624–2634.
6763. Siedlecka, A.; Wiklund, S.; Peronne, M.; Micheli, F.; Lesniewska, J.; Sethson, I.; Edlund, U.; Richard, L.; Sundberg, B.; Mellerowicz, E.J. Pectin methyl esterase inhibits intrusive and symplastic cell growth in developing wood cells of *Populus*. *Plant Physiol.* **2007**, *146*, 554–565.
6864. Bienert, M.D.; Delannoy, M.; Navarre, C.; Boutry, M. *NtSCP1* from tobacco is an extracellular serine carboxypeptidase III that has an impact on cell elongation. *Plant Physiol.* **2012**, *158*, 1220–1229.
6965. Dominguez, F.; Gonzalez, M.D.; Cejudo, F.J. A germination-related gene encoding a serine carboxypeptidase is expressed during the differentiation of the vascular tissue in wheat grains and seedlings. *Planta* **2002**, *215*, 727–734.
- ~~70.~~ Zhu, D.; Chu, W.; Wang, Y.; Yan, H.; Chen, Z.; Xiang, Y. Genome-wide identification, classification and expression analysis of the serine carboxypeptidase like protein family in poplar. *Physiol. Plantarum* **2018**, *162*, 333–352.
7466. Escamillatrevino, L.L.; Chen, W.; Card, M.L.; Shih, M.; Cheng, C.; Poulton, J.E. *Arabidopsis thaliana*  $\beta$ -glucosidases BGLU45 and BGLU46 hydrolyse monolignolglucosides. *Phytochemistry* **2006**, *67*, 1651–1660.
7267. Chapelle, A.; Morreel, K.; Vanholme, R.; Le-Bris, P.; Morin, H.; Lapierre, C.; Boerjan, W.; Jouanin, L.; Demont-Caulet, N. Impact of the absence of stem-specific  $\beta$ -glucosidases on lignin and monolignols. *Plant Physiol.* **2012**, *160*, 1204–1217.
7368. Huang, D.; Wang, S.; Zhang, B.; Shang-guan, K.; Shi, Y.; Zhang, D.; Liu, X.; Wu, K.; Xu, Z.; Fu, X.; et al. A gibberellin-mediated DELLA-NAC signaling cascade regulates cellulose synthesis in rice. *Plant Cell* **2015**, *27*, 1681–1696.
7469. Li, C.; Wang, X.; Lu, W.; Liu, R.; Tian, Q.; Sun, Y.; Luo, K. A poplar R2R3-MYB transcription factor, PtrMYB152, is involved in regulation of lignin biosynthesis during secondary cell wall formation. *Plant Cell Tiss. Org.* **2014**, *119*, 553–563.
- ~~75~~70. Guillaumie, S.; Mzid, R.; Méchin, V.; Léon, C.; Hichri, I.; Destrac-Irvine, A.; Trossat-Magnin, C.; Delrot, S.; Lauvergeat, V. The grapevine transcription factor WRKY2 influences the lignin pathway and xylem development in tobacco. *Plant Mol. Biol.* **2010**, *72*, 215–234.
7671. Yang, L.; Zhao, X.; Yang, F.; Fan, D.; Jiang, Y.; Luo, K. PtrWRKY19, a novel WRKY transcription factor, contributes to the regulation of pith secondary wall formation in *Populus trichocarpa*. *Sci. Rep.* **2016**, *6*, 18643.
- ~~77~~72. Büttner, M.; Truernit, E.; Baier, K.; Scholz-starke, J.; Sontheim, M.; Lauterbach, C.; Huss V.A.R.; Sauer, N. AtSTP3, a green leaf-specific, low affinity monosaccharide-H<sup>+</sup>symporter of *Arabidopsis thaliana*. *Plant Cell Environ.* **2000**, *23*, 175–184.
- ~~78~~73. Schneider, A.; Scholzstarke, J.; Büttner, M. Functional characterization and expression analyses of the glucose-specific AtSTP9 monosaccharide transporter in pollen of *Arabidopsis*. *Plant Physiol.* **2003**, *133*, 182–190.
- ~~79~~74. Scholz-Starke, J.; Büttner, M.; Sauer, N. AtSTP6, a new, pollen-specific H<sup>+</sup>-monosaccharide symporter from *Arabidopsis*. *Plant Physiol.* **2003**, *131*, 70–77.
8075. Schofield, R.A.; Bi, Y.; Kant, S.; Rothstein, S.J. Over-expression of *STP13*, a hexose transporter, improves plant growth and nitrogen use in *Arabidopsis thaliana* seedlings. *Plant Cell Environ.* **2009**, *32*, 271–285.
- ~~84~~76. Liu, Q.; Dang, H.; Chen, Z.; Wu, J.; Chen, Y.; Chen, S.; Luo, L. Genome-wide identification, expression, and functional analysis of the sugar transporter gene family in cassava (*Manihotesculenta*). *Int. J. Mol. Sci.* **2018**, *19*, 987.

- [8277](#). Alejandro, S.; Lee, Y.; Tohge, T.; Sudre, D.; Osorio, S.; Park, J.; Bovet, L.; Lee, Y.; Geldner, N.; Fernie, A.R.; et al. AtABCG29 is a monolignol transporter involved in lignin biosynthesis. *Curr. Biol.* **2012**, *22*, 1207–1212.
- [8378](#). Takeuchi, M.; Watanabe, A.; Tamura, M.; Tsutsumi, Y. The gene expression analysis of *Arabidopsis thaliana* ABC transporters by real-time PCR for screening monolignol-transporter candidates. *J. Wood Sci.* **2018**, *64*, 477–484.
- [8479](#). Kaneda, M.; Schuetz, M.; Lin, B.S.P.; Chanis, C.; Hamberger, B.; Western, T.L.; Ehlting, J.; Samuels, A.L. ABC transporters coordinately expressed during lignification of *Arabidopsis* stems include a set of ABCBs associated with auxin transport. *J. Exp. Bot.* **2011**, *62*, 2063–2077.
- [80](#). Hauben, M.; Haesendonckx, B.; Standaert, E.; Kelen, K.V.D.; Azmi, A.; Akpo, H.; Breusegem, F.V.; Guisez, Y.; Bots, M.; Lambert, B.; et al. Energy use efficiency is characterized by an epigenetic component that can be directed through artificial selection to increase yield. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 20109–20114.
- [81](#). Tsaftaris, A.S.; Kafka, M.; Polidoros, A.; Tani, W. Epigenetic changes in maize DNA and heterosis. In: CIMMYT. 1997. Abst. The genetics and exploitation of heterosis in crops. *Int. Symp. Mexico City* **1997**, 112–113.
- [82](#). Gourcilleau, D.; Bogeat-Triboulot, M.; Thiec, D.L.; Lafon-Placette, C.; Delaunay, A.; El-Soud, W.A.; Brignolas, F.; Maury, S. DNA methylation and histone acetylation: genotypic variations in hybrid poplars, impact of water deficit and relationships with productivity. *Ann. For. Sci.* **2010**, *67*, 208.
- [85](#). Springer, N.M. Epigenetics and crop improvement. *Trends Genet.* **2013**, *29*, 241–247.

**Table 1.** Linear correlations among phenotype parameters and between phenotype and genome methylation/non-methylation levels in xylem tissue of *Populus tomentosa*<sup>a,b</sup>.

|                     | L<br>(%) | HC<br>(%) | $\alpha$ -<br>(%) | FL<br>(mm) | FW<br>( $\mu$ m) | MFA<br>(°) | DBH<br>(cm) | H<br>(m) | V<br>(m <sup>3</sup> ) | Non-<br>(%) | CNG<br>(%) | CG<br>(%) | Uninformative<br>(%) |
|---------------------|----------|-----------|-------------------|------------|------------------|------------|-------------|----------|------------------------|-------------|------------|-----------|----------------------|
| HC (%)              | −0.229** |           |                   |            |                  |            |             |          |                        |             |            |           |                      |
| $\alpha$ -(%)       | −0.248** | 0.611**   |                   |            |                  |            |             |          |                        |             |            |           |                      |
| FL (mm)             | −0.000   | −0.012    | −0.034            |            |                  |            |             |          |                        |             |            |           |                      |
| FW ( $\mu$ m)       | −0.004   | −0.017    | −0.041            | 0.206**    |                  |            |             |          |                        |             |            |           |                      |
| MFA (°)             | −0.008   | 0.043     | 0.037             | −0.383**   | −0.093           |            |             |          |                        |             |            |           |                      |
| DBH (cm)            | 0.159**  | −0.120*   | −0.181**          | 0.280**    | 0.157**          | −0.114*    |             |          |                        |             |            |           |                      |
| H (m)               | 0.083    | −0.001    | −0.095            | 0.246**    | −0.001           | −0.143**   | 0.634**     |          |                        |             |            |           |                      |
| V (m <sup>3</sup> ) | 0.134**  | −0.080    | −0.161**          | 0.273**    | 0.095            | −0.085     | 0.945**     | 0.728**  |                        |             |            |           |                      |
| Non-(%)             | 0.010    | −0.011    | −0.049            | −0.039     | 0.037            | 0.015      | 0.010       | −0.109*  | −0.049                 |             |            |           |                      |
| CNG(%)              | 0.035    | 0.028     | 0.032             | 0.016      | −0.002           | 0.041      | −0.064      | 0.002    | −0.021                 | −0.741**    |            |           |                      |
| CG(%)               | −0.039   | 0.011     | 0.017             | 0.056      | 0.071            | −0.005     | 0.077       | 0.122*   | 0.096                  | −0.413**    | 0.356**    |           |                      |
| CG/CNG(%)           | −0.032   | −0.017    | 0.032             | 0.014      | −0.088           | −0.060     | 0.009       | 0.097    | 0.044                  | −0.518**    | −0.103*    | −0.254**  |                      |
| Total(%)            | 0.013    | 0.026     | 0.032             | 0.035      | 0.027            | 0.030      | −0.019      | 0.051    | 0.022                  | −0.748**    | 0.931**    | 0.671**   | −0.181**             |

<sup>a</sup>Abbreviations: L, lignin; HC, holocellulose;  $\alpha$ -,  $\alpha$ -cellulose; FL, fiber length; FW, fiber width; MFA, microfibril angle; DBH, diameter at breast height; H, height of tree; V, volume of timber; Non-, relative non-methylation level; CNG, relative hemi-methylation level; CG, relative full-methylation level; Uninformative, relative level of uninformative site.

<sup>b</sup>The primary percentage data were transformed as  $x_{ij} = \arcsin \sqrt{x_{ij}}$  before calculation.

\*  $P < 0.05$  (2-tailed), \*\*  $P < 0.01$  (2-tailed).