

RESEARCH

Open Access



Characterization of the pyruvate kinase gene family in soybean and identification of a putative salt responsive gene GmPK21

Wei Liu^{1,2}, Yubin Wang^{1,2}, Yanwei Zhang^{1,2}, Wei Li^{1,2}, Caijie Wang^{1,2}, Ran Xu^{1,2}, Haiying Dai^{1,2} and Lifeng Zhang^{1,2*}

Abstract

Background As a key regulatory enzyme in the glycolysis pathway, pyruvate kinase (PK) plays crucial roles in multiple physiological processes during plant growth and is also involved in the abiotic stress response. However, little information is known about PKs in soybean.

Results In this study, we identified 27 PK family genes against the genome of soybean cultivar Zhonghuang13. They were classified into 2 subfamilies including PKc and PKp. 22 segmental duplicated gene pairs and 1 tandem duplicated gene pair were identified and all of them experienced a strong purifying selective pressure during evolution. Furthermore, the abiotic stresses (especially salt stress) and hormone responsive *cis*-elements were present in the promoters of GmPK genes, suggesting their potential roles in abiotic stress tolerance. By performing the qRT-PCR, 6 GmPK genes that continuously respond to both NaCl and ABA were identified. Subsequently, GmPK21, which represented the most significant change under NaCl treatment was chosen for further study. Its encoded protein GmPK21 was localized in the cytoplasm and plasma membrane. The transgenic *Arabidopsis* overexpressing GmPK21 exhibited weakened salinity tolerance.

Conclusions This study provides genomic information of soybean PK genes and a molecular basis for mining salt tolerance function of PKs in the future.

Keywords Soybean, Pyruvate Kinase gene family, Genome identification, Salt stress Overexpression

Background

As an important metabolic pathway, glycolysis widely exists in higher plants and animals. Pyruvate Kinase (PK) is a key regulatory enzyme in the glycolysis pathway. It catalyzes the last step of glycolysis by transferring the high-energy phosphate group of phosphoenolpyruvates

to adenosine diphosphate (ADP), and then produces ATP and pyruvate [1]. Pyruvate then acts as an important substance in organisms to participate in multiple metabolic reactions [2].

In plants, there are two isoenzymes of PKs in cytoplasm and plastid respectively, namely PKc and PKp [3]. They are different in physics, dynamics, immunology and expression regulation [3–7]. The PKs acting as PKc or PKp were found to be involved in multiple development and growth processes. It was reported that several PK genes in *Arabidopsis* were involved in oil and fatty acid biosynthesis in seeds [8, 9]. In tobacco, absence of leaf PKc resulted in a striking decrease in root biomass

*Correspondence:

Lifeng Zhang
zhanglifeng9639@sina.com

¹ Crop Research Institute, Shandong Academy of Agricultural Sciences, 202 Gongye North Road, Jinan 250100, Shandong, China

² Shandong Engineering Laboratory of Featured Crops, 202 Gongye North Road, Jinan 250100, Shandong, China



©The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

and root: shoot ratios [10]. Similarly, *GhPK6* in cotton played an important role in regulating cotton fiber elongation [11]. Compared with other plants, *PK* genes have been studied more systematically in rice. For instance, downregulation of *OsPK1* causes dwarfism and panicle enclosure in rice [12]; *OsPK5* is involved in rice glycolytic metabolism and GA/ABA balance for improving seed germination [13]. Furthermore, several *PK* genes were reported to be involved in the grain filling of rice [14–16].

With the development of transcriptomics and proteomics technology, the expression of *PK* genes or the accumulation of *PK* protein in plants suffering from abiotic stress were found to be affected. *AhABI4s* negatively regulate salt-stress response in peanut. The transcriptomics and quantitative proteomics analyses showed that *PKs* and other genes/proteins were affected by silencing of *AhABI4s* in peanut leaf and root after NaCl treatment. Furthermore, *AhABI4s* were able to bind to the promoters of pyruvate kinase (*PK*) coding genes in vitro [17]. In soybean, pyruvate kinase was increased under flooding, but gradually decreased during post-flooding recovery period at protein abundance, mRNA, and enzyme activity levels [18]. In pepper, the expression of *CaPKc1* gene was not only increased when the plants were infected by *Tobacco mosaic virus* (TMV), but also triggered by NaCl and wounding [19]. In *Brassica napus*, *PKs* showed an increased abundance under freezing stress after cold acclimation [20]. These reports suggest that *PKs* might be involved in the abiotic stress responses. However, the study of the *PKs* function in the abiotic stress tolerance is very limited. The only report is about a rice *PK* gene *OsPK5*. It could interact with *OsSAP6*, a member of stress-associated protein (*OsSAP*) gene family which could positively regulates saline-alkaline tolerance. Furthermore, overexpression of *OsPK5* in rice enhanced tolerance to soda saline-alkaline stress at seedling stage [21].

Soybean (*Glycine max* [L.] Merr.) is the leading oilseed crop produced and consumed in the world [22]. However, the production of soybean is severely threatened by the abiotic stresses, such as high salt [23]. Although the *PK* gene family has been identified and analyzed in *Arabidopsis* and rice [24, 25], little information is known about *PK* proteins in soybean. In this study, we performed genome-wide characterization of the soybean *PK* family genes against a reference soybean genome of a soybean cultivar, Zhonghuang13 [26] and analyzed their expression patterns under NaCl and ABA treatment. Furthermore, *GmPK21*, which was represented the most significant change under NaCl treatment was chosen for further study. The gene function analysis of *GmPK21* showed that it had a negative regulatory effect on salt stress tolerance in *Arabidopsis*. This research lays

a foundation for further function investigations of *PK* genes in soybean.

Results

Identification and phylogenetic analysis of *PK* genes in soybean

We identified 27 soybean *PK* genes in this study (Table 1; Table S1). Those 27 soybean *PK* genes were named from *GmPK1* to *GmPK27*. The predicted protein products of these 27 *GmPK* genes varied from 184 (*GmPK3*) to 582 (*GmPK16* and *GmPK24*) amino acids. The protein MW (Molecular Weight) of these 27 *GmPK* proteins ranged from 20.06 kDa (*GmPK3*) to 63.68 kDa (*GmPK20*). Their predicted PI (isoelectric points) varied from 4.52 (*GmPK3*) to 8.01 (*GmPK7*). The protein sequences of 27 *GmPK* genes were shown in Table S1.

We then built a phylogenetic tree by analyzing the amino acid sequences with the *PK* proteins from soybean, *Arabidopsis* and rice. Based on the phylogenetic analysis and previous research [24, 25], all of the *PK* proteins were divided into 2 subfamilies, *PKc* and *PKp*. The *PKc* subfamily was further divided into *PKc-1* and *PKc-2* clade. Similarly, the *PKp* subfamily was divided into *PKp-α* and *PKp-β* clade. As shown in Fig. 1, 11 *GmPKs* belonged to the *PKp* subfamily. Among them, 7 belonged to *PKp-β* clade and the other 4 belonged to *PKp-α* clade. The *PKc* subfamily contained 16 *PKs*. Of them, 7 were *PKc-1* genes, and the other 9 were *PKc-2* genes (Fig. 1).

Chromosomal distributions, duplications and synteny analysis of the *GmPK* genes

These 27 *GmPK* genes were distributed on 13 out of the 20 chromosomes. The chromosome 10 (Chr 10) and 20 contained the largest number of *GmPK* genes (both of them had 5 *GmPK* genes), followed by Chr 2 and 5 each containing 3 *GmPK* genes. No *GmPK* genes were identified on Chr 4, 6, 12, 14, 15, 17 and 18 (Fig. 2).

Tandem and segmental duplications play important roles in the expansion of plant gene families [27]. To reveal the expansion mechanism of the *GmPK* gene family, the gene duplication events of the soybean *PK* genes were investigated. We found that only 1 pair of soybean *PK* genes was tandem repeat. 22 pairs of soybean *PK* genes were found to be segmental duplications (Fig. 3; Table S2). The nonsynonymous (Ka) and synonymous (Ks) substitution rates between these duplicated gene pairs were also calculated. The Ka/Ks of all the 23 duplicated gene pairs was found to be less than 1, suggesting that the soybean *PK* gene family might have experienced a strong purifying selective pressure during evolution (Table S2).

To detect the synteny of *GmPK* genes, a collinearity analysis between soybean and the other 2 plant species,

Table 1 List of pyruvate kinase family genes from soybean

Gene Name	Gene ID	Protein Length	Molecular weight (kD)	Isoelectric point
GmPK1	SoyZH13_01G183800.m1	545	60.28	7.69
GmPK2	SoyZH13_02G067000.m1	412	44.78	6.19
GmPK3	SoyZH13_02G067100.m1	184	20.06	4.52
GmPK4	SoyZH13_02G153600.m1	527	57.66	6.74
GmPK5	SoyZH13_03G170700.m1	527	57.66	7.09
GmPK6	SoyZH13_05G000800.m1	511	55.3	7.63
GmPK7	SoyZH13_05G076500.m1	265	29.49	8.01
GmPK8	SoyZH13_05G088000.m1	384	42.17	6.74
GmPK9	SoyZH13_07G210000.m1	501	54.29	7.66
GmPK10	SoyZH13_08G215000.m1	220	23.95	7.2
GmPK11	SoyZH13_09G112500.m1	577	63.34	7.65
GmPK12	SoyZH13_10G061700.m1	527	57.65	7.57
GmPK13	SoyZH13_10G163800.m1	569	62.88	6.01
GmPK14	SoyZH13_10G185200.m1	526	57.88	7.4
GmPK15	SoyZH13_10G209900.m1	543	59.79	7.01
GmPK16	SoyZH13_10G235900.m1	582	63.43	5.31
GmPK17	SoyZH13_11G041200.m1	310	34.92	6.56
GmPK18	SoyZH13_13G130400.m1	527	57.6	6.9
GmPK19	SoyZH13_16G135700.m1	502	54.76	6.36
GmPK20	SoyZH13_16G154700.m1	577	63.68	6.98
GmPK21	SoyZH13_19G000600.m1	510	55.24	7.63
GmPK22	SoyZH13_19G175100.m1	527	57.57	7.57
GmPK23	SoyZH13_20G023700.m1	502	54.34	7.22
GmPK24	SoyZH13_20G122100.m1	582	63.65	5.7
GmPK25	SoyZH13_20G150700.m1	575	63.17	7.29
GmPK26	SoyZH13_20G174800.m1	526	57.92	6.79
GmPK27	SoyZH13_20G196600.m1	567	62.52	6.21

including 1 monocot (rice) and 1 dicot (*Arabidopsis*) was performed. A total of 15 and 4 soybean PK genes showed a syntenic relationship with those in *Arabidopsis* and rice, respectively (Table S3). This finding suggests that soybean PK genes display a higher evolution divergence with monocotyledonous plants. Notably, we found 2 GmPK genes (GmPK19 and GmPK22) were collinear with the PK genes from both of the *Arabidopsis* and rice (Table S3), suggesting that they might play important roles during the evolution of GmPK genes.

Gene structure and conserved protein motif analysis of GmPK genes

By performing the multiple sequence alignment, we found that all of the 27 GmPKs shared the typical PK domain (Figure S1). Then the MEME program was used to detect conserved motifs in the GmPK gene family. 10 distinct motifs (named motif 1–10) were identified (Fig. 4b, Figure S2). Among them, Motif 1, 2, 3, 6, 7 and 10 belonged to the PK domain, motif 4 (or 5), 7 and 8

belonged to PK_C domain. In general, proteins from the same subfamily or clade were characterized by a similar motif type and distribution (Fig. 4a and b). Almost all of the PKc (including PKc-1 and PKc-2 clade) subfamily members (except GmPK2, GmPK3, GmPK7 and GmPK8) contained motif 3, 7, 6, 10, 2, 1, 9, 4 and 8. All the members in PKp- α clade contained the motif 3, 7, 6, 10, 2, 1 and 4. We also noticed that the motif 8 and 9 can only be detected in PKc subfamily, and motif 5 was only observed in the PKp- β clade.

In order to examine the gene structures, the exon–intron structures of the 27 GmPK genes were analyzed. As shown in Fig. 4c, the number of introns varied greatly between the clades of the same subfamily. The introns number of PKc-2 clade ranged from 8 to 15. However, the introns number of PKc-1 clade members ranged from 1 to 4. Almost all of the GmPK genes in PKp- β clade contained 11 introns (except GmPK10 and GmPK17), while the GmPK genes in PKp- α clade only contained 5 or 6 introns.

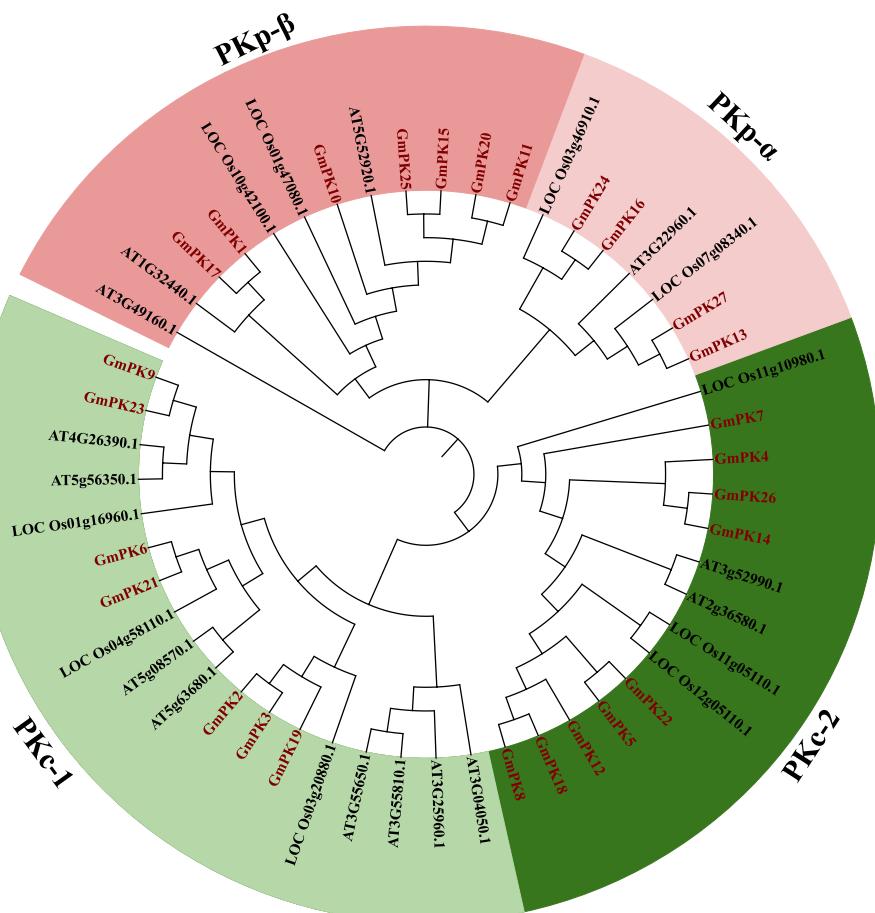


Fig. 1 Phylogenetic tree based on protein sequences of *PK* genes in soybean, *Arabidopsis* and rice (At, *Arabidopsis thaliana*; Os, *Oryza sativa*)

Expression profiling of *PK* genes in different tissues of soybean

In order to investigate the transcript abundance of *PK* genes in different tissues, expression of the 27 *GmPK* genes covering 7 tissues of soybean was performed by qRT-PCR. Based on their expression pattern, the *GmPK* genes could be generally classified into 4 groups (Fig. 5). Genes in group 1 were barely detected in more than 5 soybean tissues. The genes in group 2 could be detected in more than 5 tissues, but the expression level was relative lower. There was a trend that all of those 3 genes in group 3 were highly expressed in all of the 7 tissues, and the 10 genes in group 4 were expressed with moderate level in almost all of the tissues (Fig. 5). Furthermore, several *GmPK* genes were found to display higher expression level in particular tissues. For example, *GmPK22*, *GmPK6*, *GmPK26* and *GmPK14* exhibited higher expression levels in roots than other tissues. The expression of *GmPK24*, *GmPK1* and *GmPK12* were relatively higher in cotyledon than in other tissues (Fig. 5).

Cis-acting regulatory element analysis

To further understand the transcriptional regulation mechanisms of *GmPK* genes, we characterized the *cis*-acting regulatory elements within a 1500 bp upstream region from the transcription start site. As shown in Fig. 6 and supplementary Table S4, *cis*-elements related to abiotic stresses were identified, including the anaerobic responsive element (ARE), salt-regulated elements (SRE, GT1GMSCAM4), drought responsive elements (MYB binding site involved in drought-induction (MBS)) and low temperature responsive element (LTR). Several other regulatory elements associated with plant hormones were also detected, such as abscisic acid responsive element (ABRE), Auxin response element (AuxRR-core), gibberellin-responsive element (GARE-motif), methyl jasmonate (MeJA)-responsive element (CGTCA motifs), salicylic acid responsive element (TCA-element) and ethylene-responsive element (ERE). Of these abiotic stresses and hormone-responsive elements, the salt-regulated element (SRE, GT1GMSCAM4) was present in 25 out of the 27 promoters, being the most prevalent *cis*-element.

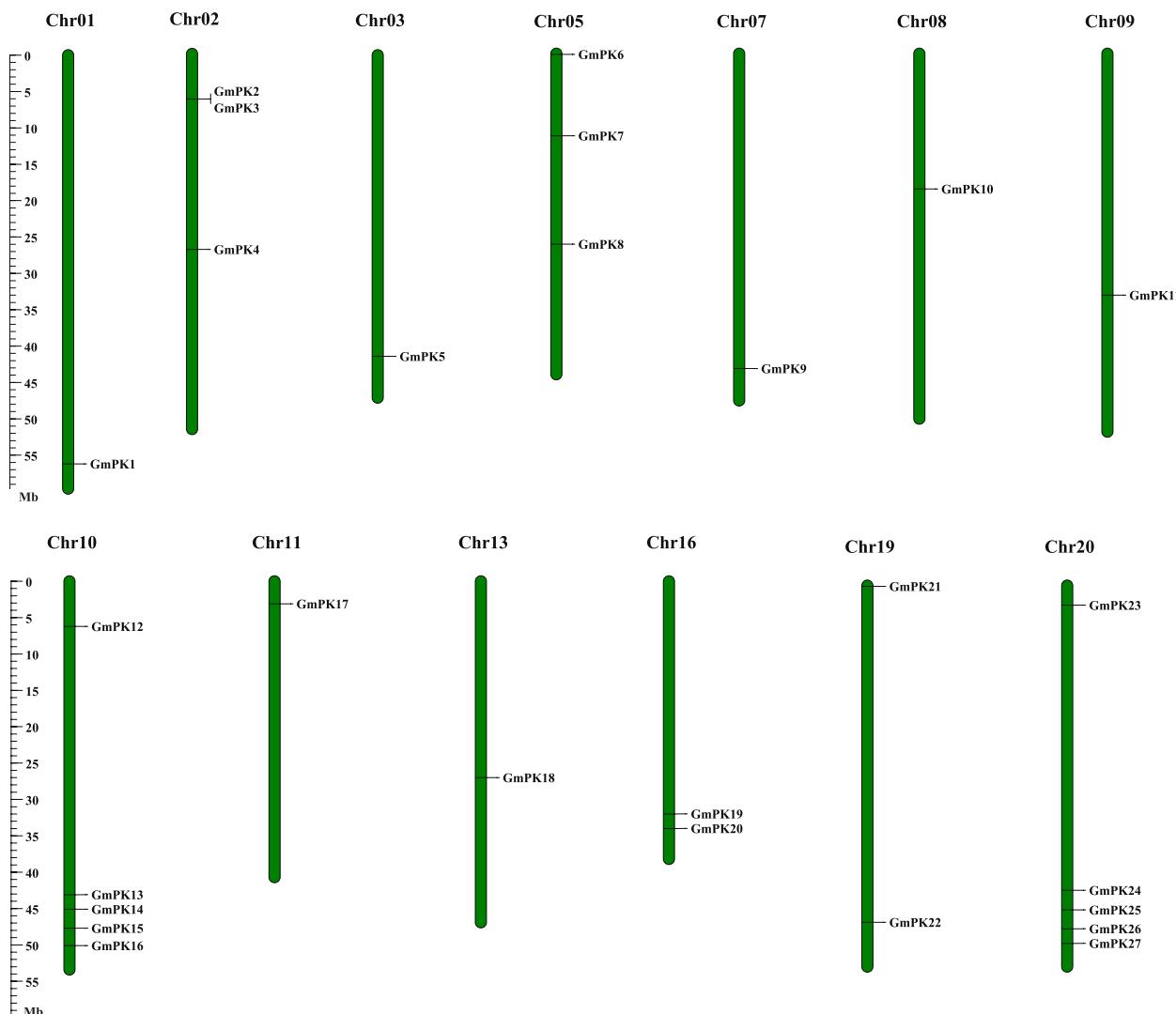


Fig. 2 The chromosomal locations of *PK* genes in soybean. Green bars represent the 20 soybean chromosomes. The chromosome numbers are presented at the tops of the green bars. Scale bar on the left represents the lengths of each chromosome (Mb). Chr: Chromosome

(Fig. 6b, Table S4). These results might imply that the *GmPK* genes could be regulated by hormones and abiotic stresses, especially the salt stress. Furthermore, the promoters of the *GmPK* genes contained predicted binding sites for several transcription factors, including MYB (23 out of 27 promoters), MYC (24 out of 27 promoters) and WRKY (11 out of 27 promoters) (Fig. 6; Table S4).

Expression profiles of *GmPK* genes in response to salt stress and ABA treatment

In order to identify the salt-responsive *GmPK* genes in soybean, we performed qRT-PCR of all the 27 *GmPK* genes when the roots of soybean suffered from NaCl treatment at seedling stage. As shown in Fig. 7, the expression of 24 *GmPK* genes were found to be

significantly changed in at least 1 time point. Among them, 16 genes were up-regulated by NaCl treatment, while 7 genes were down-regulated. 1 gene (*GmPK1*) was down-regulated at 3 h, but was up-regulated at 6 and 12 h. Notably, 15 *GmPK* genes were differently expressed at all of the 3 time-points (Fig. 7).

We next examined the expression of these 15 *GmPK* genes which respond to NaCl at all of the 3 time point under 100 μM ABA treatment. The result displayed that the expressions of 6 *GmPK* genes (*GmPK4*, *GmPK11*, *GmPK14*, *GmPK17*, *GmPK21* and *GmPK26*) which were continuously regulated by salt were also significantly changed at all of the 3 time-points under ABA treatment (Fig. 8). Among them, the expression of *GmPK21* was represented the most significant change under NaCl

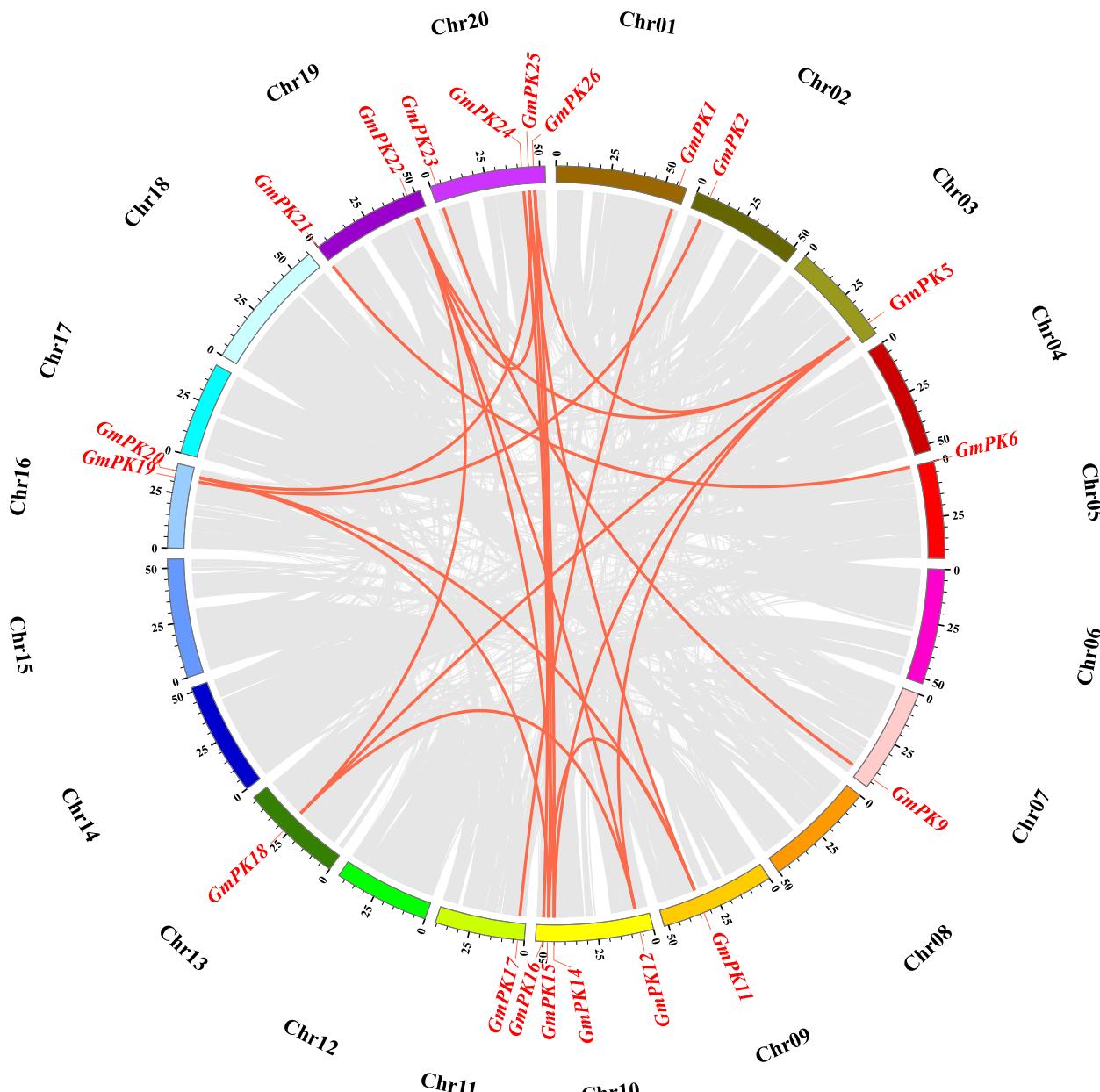


Fig. 3 Circle plot of soybean chromosomes and the *GmPK* genes displayed as segmental duplicated gene pairs. The *GmPK* gene pairs are indicated by the red lines. Scale bar in marked on the chromosome indicates the chromosome lengths (Mb). Chr: Chromosome

treatment (Fig. 7), being the best candidate for further study.

Expression of *GmPK21* and subcellular localization of its protein GmPK21

In order to clarify the details of the expression of *GmPK21*, the tissue expression pattern of *GmPK21* was analyzed by histochemical GUS staining of transgenic *Arabidopsis* in which the *GUS* gene was driven by the

promoter of *GmPK21*. As shown in Fig. 9 a-c, the GUS signal could be detected in leaves, roots, shoot apical, calyx and siliques, which is consistent with the expression pattern of *GmPK21* in different tissues of soybean measured by qRT-PCR (Fig. 5). Moreover, *GmPK21* was found to be highly expressed in vascular of the tested tissues. We then performed the GUS staining of the root when the plants were treated by 100 mM NaCl. The result showed that the GUS signal was significantly stronger than control

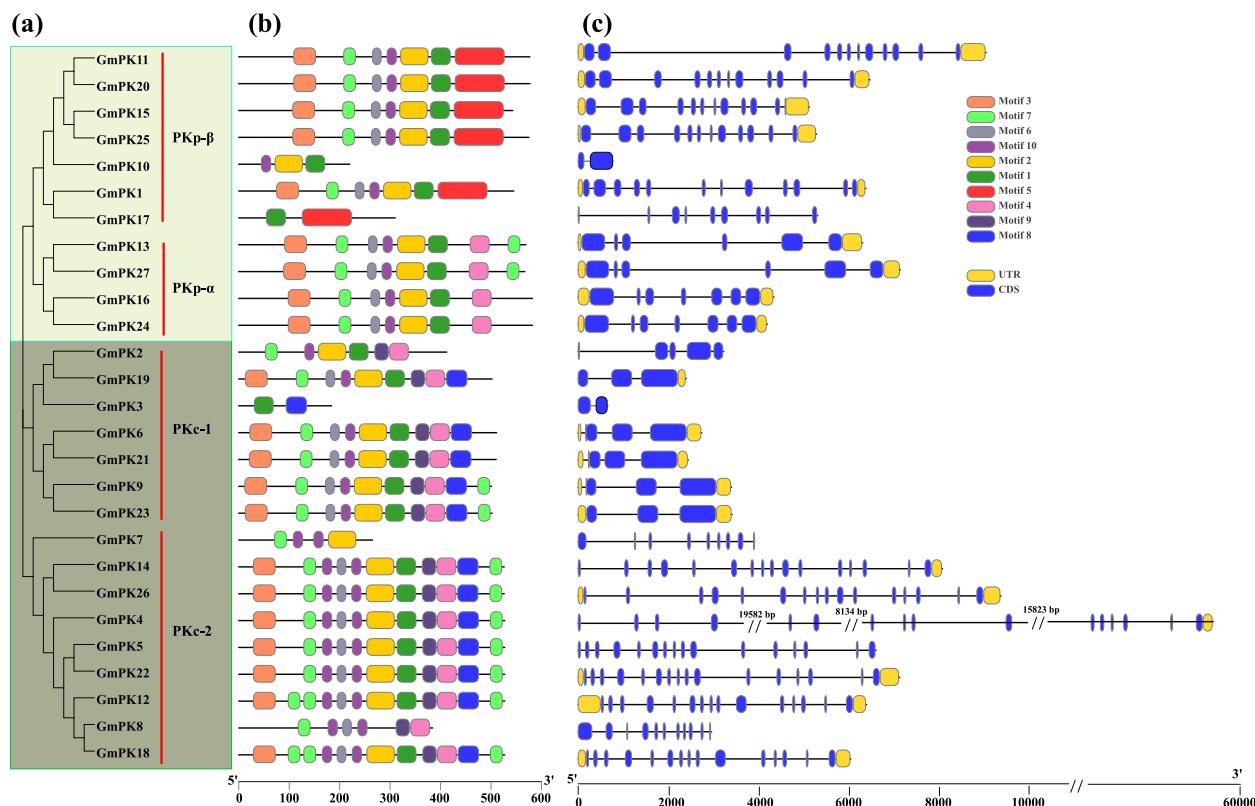


Fig. 4 Conserved motifs and gene structures of *GmPKs*. **a** Phylogenetic tree based on protein sequences of PK genes in soybean. **b** Conserved motifs of GmPKs. The details of the motif were shown in Figure S2. **c** The gene structures of *GmPK* genes. CDS, introns, and untranslated regions (UTRs) are indicated by yellow boxes, black lines, and green boxes, respectively

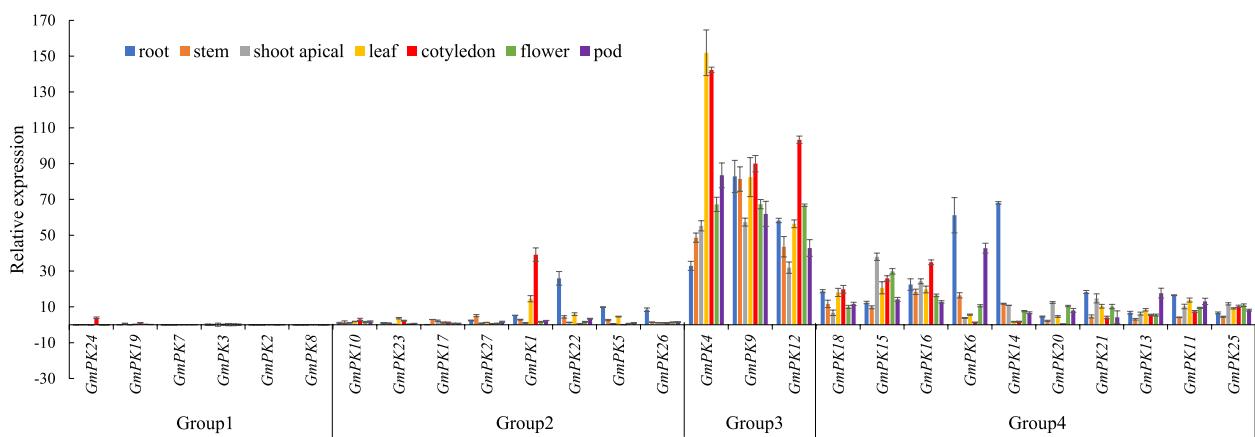


Fig. 5 The expression profiles of the soybean PK genes in different tissues examined by qRT-PCR. The error bar represents the mean \pm SD of three biological replicates

(Fig. 9 d-e), which is consist with the fact that *GmPK21* could be upregulated by NaCl treatment (Fig. 7).

In order to explore the subcellular localization of *GmPK21*, the *GmPK21*-GFP fusion protein was

transformed into *Arabidopsis* protoplast (Fig. 9f) and tobacco protoplast (Figure S3). The result showed that the green fluorescent signal of *GmPK21* was detected in the cytoplasm and plasma membrane (Fig. 9f, Figure S3).

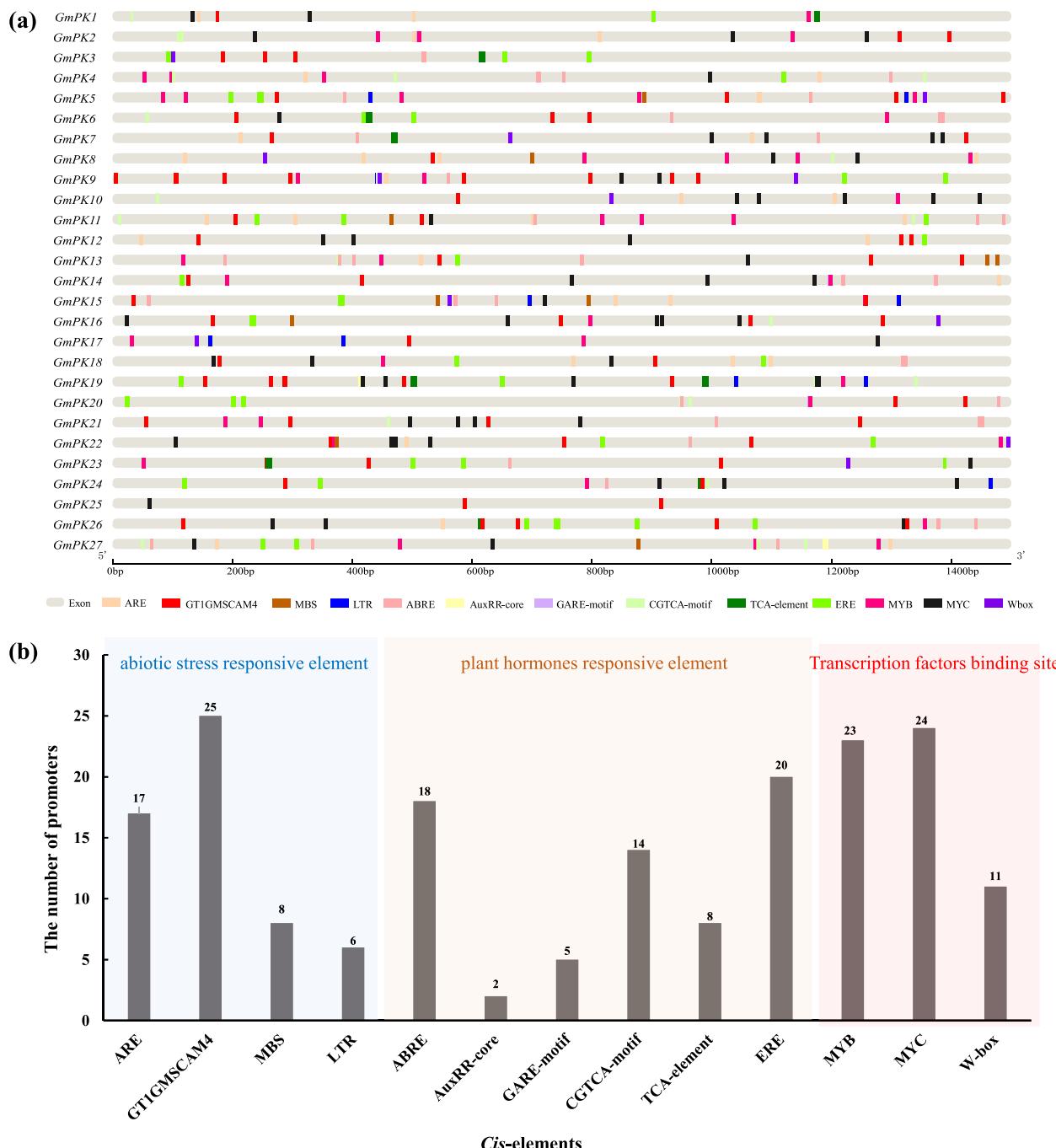


Fig. 6 Cis-acting regulatory element analysis of *GmPK* genes. **a** Diagram of cis-acting regulatory elements in promoters of *GmPK* genes; **b** The distribution of the cis-elements related to abiotic stresses, plant hormones and transcription factors binding site. ARE: anaerobic responsive element; GT1GMSCAM4: salt-regulated element; MBS: drought responsive element; LTR: low temperature responsive element; ABRE: abscisic acid responsive element; AuxRR-core: Auxin response element; GARE-motif: gibberellin-responsive element; CGTCA-motif: methyl jasmonate (MeJA)-responsive element; TCA-element: salicylic acid responsive element; ERE: ethylene responsive element. W-box: WRKY binding site

Ectopic expression of *GmPK21* in *Arabidopsis* reduced the plant salt tolerance

To investigate the role of *GmPK21* in salt tolerance, *GmPK21* was overexpressed in *Arabidopsis*. 3 transgenic

lines displayed higher PK enzyme activity compared to WT were further used to perform NaCl treatment assay (Fig. 10a). The seedlings of the transgenic line 4 and 8 displayed similar growth status with wild type (WT), and

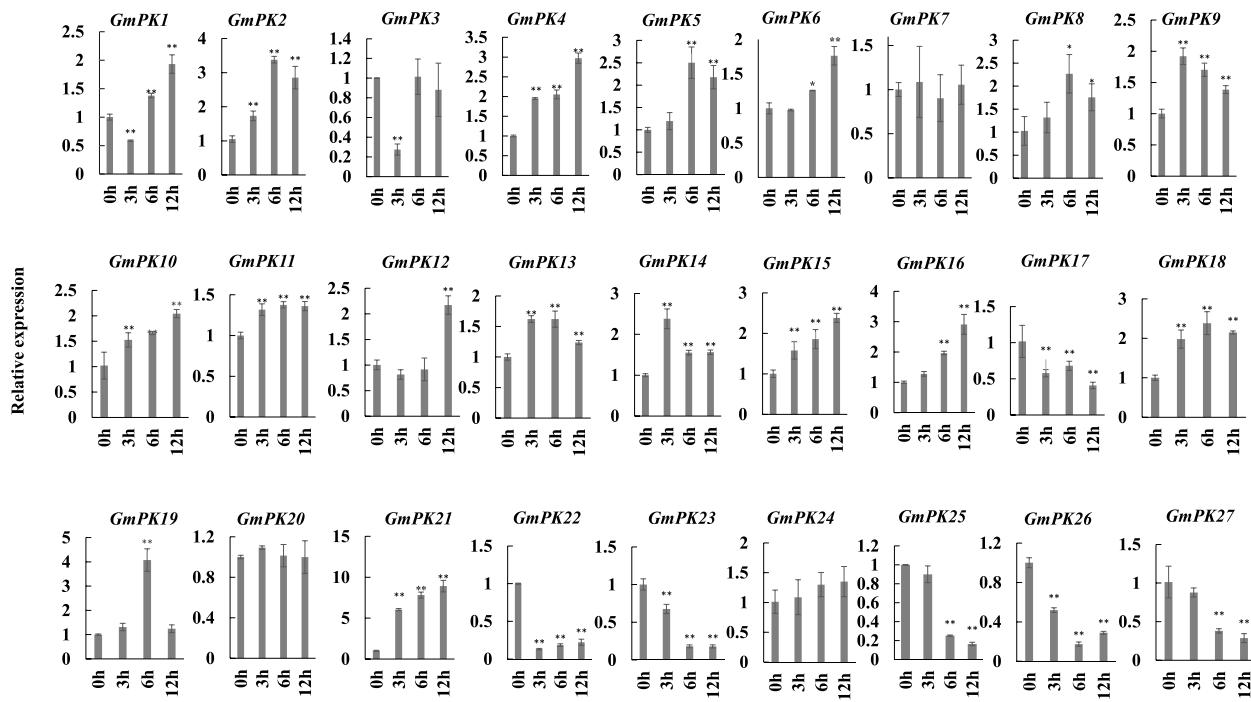


Fig. 7 The expression of all the 27 GmPK genes under 200 mM NaCl treatment. The error bar represents the mean \pm SD of three biological replicates. Student's t-test was used to examine the statistical significance (** $p < 0.01$, * $p < 0.05$)

the L10 showed slightly longer primary roots compared with WT on 1/2 MS medium (Fig. 10 b-c). However, when the 3-day-old seedlings were transferred to the 1/2 MS medium containing 200 mM NaCl, the growth status of all the 3 transgenic lines was weaker than WT, and the primary roots were shorter than WT (Fig. 10 b-c).

We further verified the salt tolerance of transgenic *Arabidopsis* in soil. The 21-day-old seedlings were subjected to 200 mM NaCl for 19 days. The growth status and the fresh weights of the up-ground part of the seedlings were similar between the transgenic *Arabidopsis* and WT under normal condition. However, after 19 days NaCl treatment, the seedlings of transgenic lines grew significantly slower and weaker than WT, and the fresh weight of the aboveground parts of transgenic seedlings were much lower than that of WT (Fig. 10 d-e). The accumulations of proline could assist plants to resist the environmental stresses [28], and the MDA content is an important indicator of the degree of membrane lipid peroxidation and plasma membrane damage in plant cells. Therefore, we measured the Proline (Pro) and malondialdehyde (MDA) contents of the transgenic and WT seedlings. The Pro and MDA contents of all the seedlings didn't show significant difference between transgenic *Arabidopsis* and WT under normal condition. However, 19 days after NaCl treatment, the accumulation of Pro and MDA in transgenic plants and WT was significantly

promoted compared to that under normal condition. Moreover, the Pro content in transgenic *Arabidopsis* were significantly lower than that in WT seedlings, while the MDA content in transgenic *Arabidopsis* were significantly higher than that in WT (Fig. 10 f-g).

Discussion

Pyruvate Kinase is a key regulatory enzyme in the glycolysis pathway. However, little information is known about PK genes in soybean. In this study, we identified 27 PK genes which were distributed in 13 out of the 20 chromosomes of soybean. The number of soybean PK genes is more than that in *Arabidopsis* (14), rice (10), potato (11) [29] and cotton (33) [11]. By examining the genome size and the density (number/Mb) of PK genes of the species above, we found that the density of PK genes in the soybean genome (0.03) is less than that in *Arabidopsis* (0.10) and potato (0.11), but similar to that in rice (0.03) and cotton (0.02). The differences in PK gene number and density between species might due to gene duplication events or the genome size [27, 30]. The soybean PK family genes were classified into 2 distinctive subfamilies PKc and PKp and each of them was further divided into two subclades. The result is consistent with the classification reported in *Arabidopsis* and rice [24, 25].

Gene duplication is one of the major evolutionary mechanisms for gene expansion [27, 31]. In general,

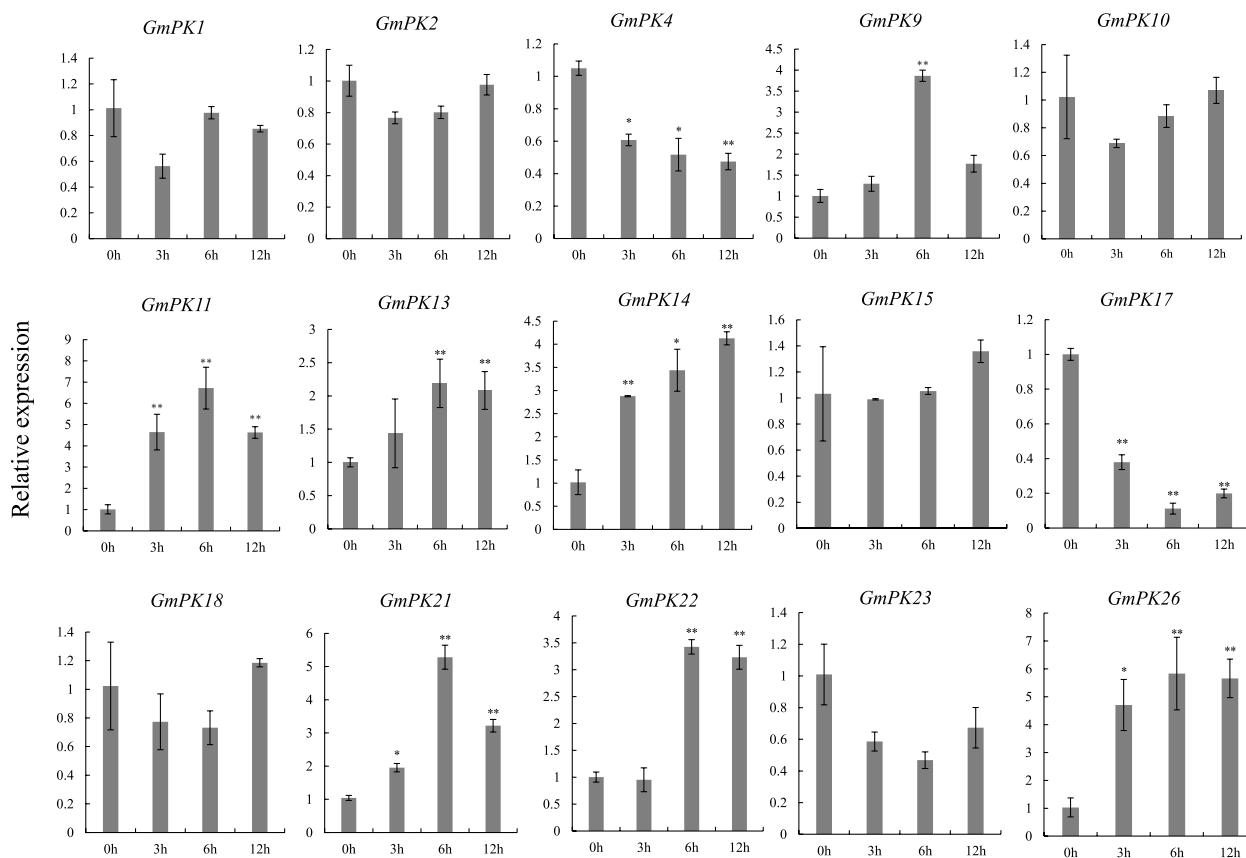


Fig. 8 The expression of the 15 NaCl responsive *GmPK* genes under 100 μ M ABA treatment. The error bar represents the mean \pm SD of three biological replicates. Student's t-test was used to examine the statistical significance (** $p < 0.01$, * $p < 0.05$)

gene families expand mainly by tandem and segmental duplications [27]. In our study, 22 pairs segmental duplicated gene (involved in 20 genes) representing 74.07% of the total 27 *GmPK* genes were identified. Therefore, the segmental duplication is the main mechanism of *GmPK* genes duplication. The soybean genome has undergone two rounds of whole genome duplication events, including the Legume WGD at around 59 million years ago ($K_s < 0.3$) and the Glycine WGD at around 13 million years ago ($0.3 < K_s < 1.5$) [32]. In the present study, half of the duplication events occurred during the Glycine genus WGD (whole-genome duplication) event, 8 gene pairs were separated during the legume WGD event. The duplication has contributed to adaptive evolution in plants [33]. Duplication gene pairs will experience different selection process, including subfunctionalization through purifying selective pressure ($K_a/K_s < 1$) [34] and neofunctionalization through positive selective pressure ($K_a/K_s > 1$) [35]. In soybean, most of the duplicated genes are subfunctionalized, only a small proportion of the duplicated genes have been neofunctionalized or non-functionalized [36]. In this study, all of the K_a/K_s ratios

in different *PK* gene pairs were less than 1, suggesting that all of those duplicated *PK* genes were experienced a strong purifying selective pressure and subfunctionalized during evolution.

GmPK proteins from the same subfamily displayed similar motif type and distribution (Fig. 4). That is, the *GmPKs* of PKc-1 and PKc-2 had similar motif, and the *GmPKs* from PKp- α and PKp- β also had similar motif. However, the gene structures between each clade were different. The introns of PKc-2 genes are much more than those of PKc-1 genes, and the introns of PKp- β genes are much more than those of PKp- α genes (Fig. 4). This finding is consistent with that of the *PKs* in rice [25]. The results might indicate that the *PK* genes have changed the numbers and the length of introns to adapt to the environment during their evolutionary process but retained their conserved domains, which enabled the genes to perform their functions stably [25]. The genes expression patterns in different tissues provide clues to mining the potential function of these genes. In this study, a number of *GmPK* genes were constitutively expressed in most of the tested tissues, suggesting that they might

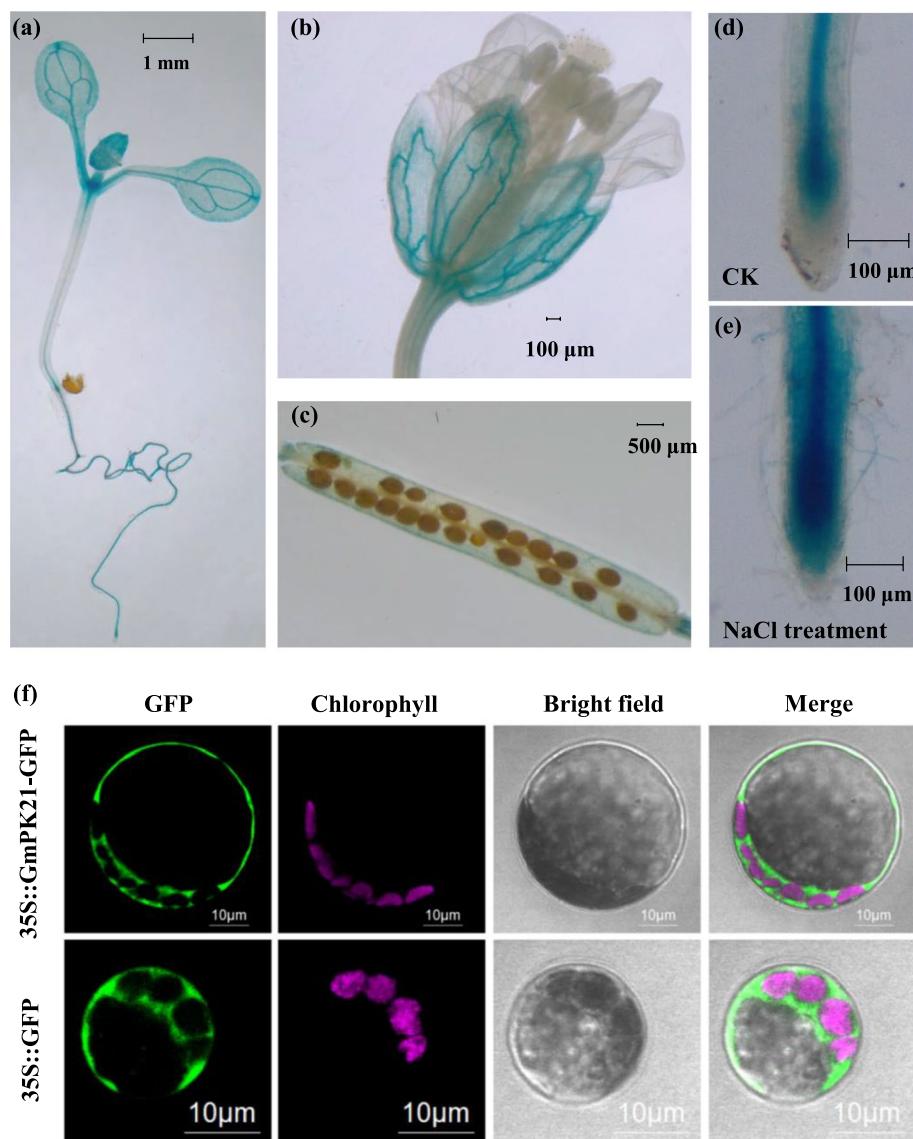
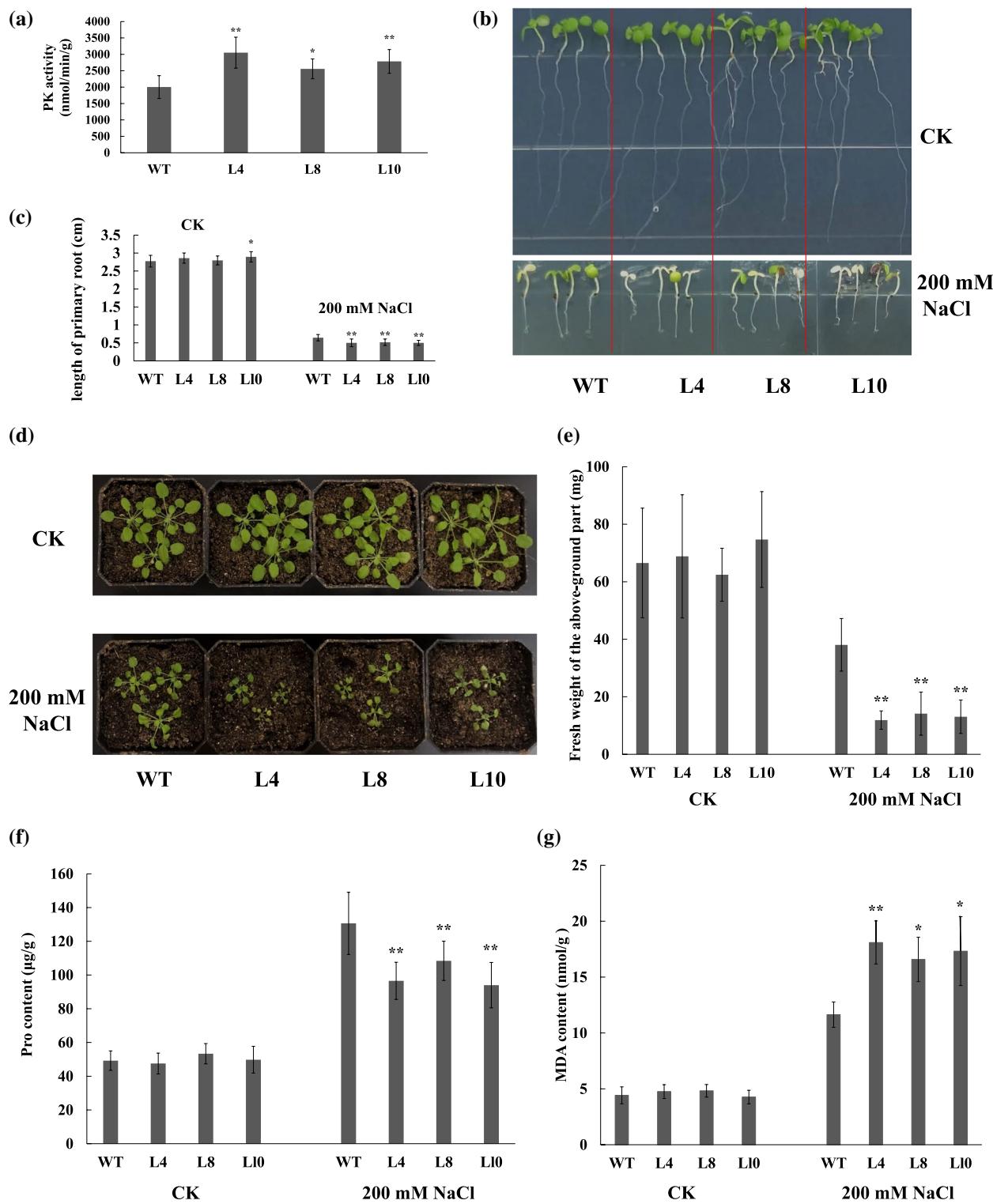


Fig. 9 The expression pattern of *GmPK21* and subcellular localization of *GmPK21*. **a-c** The GUS activity in the different tissues of *GmPK21pro:GUS* transgenic *Arabidopsis*. **d** and **e** The GUS activity in the roots of *GmPK21pro:GUS* transgenic *Arabidopsis* treated by 100 mM NaCl for 6 h (**e**) and CK (**d**). **f** The subcellular localization of a *GmPK21-GFP* in *Arabidopsis* protoplasts

(See figure on next page.)

Fig. 10 The phenotype of the 35S:*GmPK21* transgenic *Arabidopsis* plants under NaCl treatment. **a** The pyruvate kinase activity of *GmPK21* in the wild type (WT) and the 35S:*GmPK21* transgenic *Arabidopsis* plants. **b** and **c** An overview (**b**) and the primary root length (**c**) of the wild type seedlings and the 35S:*GmPK21* transgenic *Arabidopsis* seedlings grown in 1/2 MS with or without 200 mM NaCl. **d** The phenotype of the WT and transgenic *Arabidopsis* grown in soil under normal condition or under 200 mM NaCl treatment. **e** The fresh weight of the WT and transgenic *Arabidopsis* grown under normal condition or under NaCl treatment. **f** The proline (Pro) and (**g**) malondialdehyde (MDA) contents of the transgenic and WT seedlings grown under normal condition or under 200 mM NaCl treatment. The data are means \pm SD, and statistical significance was determined using Student's t-tests: **, $P < 0.01$, *, $P < 0.05$. WT: the wild type *Arabidopsis*; L4, L8 and L10 represent 3 transgenic *Arabidopsis* lines overexpressed *GmPK21*

**Fig. 10** (See legend on previous page.)

play multiple roles during the development of soybean. In rice, a PKc-2 subclade gene *OsPK1* (*LOC_Os11g05110*) was reported to be involved in the plant morphological

development. The *ospk1* mutant displayed later germination, shorter shoots, roots, leaves and internode and also showed marked reductions in seed number per panicle

and seed set [12]. In the present study, 2 PKc-2 subclade member *GmPK4* and *GmPK12* were expressed in all of these tested tissues with a remarkable transcription level. This finding suggests that *GmPK4* and *GmPK12* might also be involved in the regulation of soybean morphological development. In *Arabidopsis*, *AtPKp1* (*At3g22960*) was reported to be involved in seed oil accumulation, embryo development and seed storage compounds mobilization upon germination [8, 9, 37]. Here, a soybean PK gene *GmPK13* which is homologous to *AtPKp1* exhibited a higher expression in pod, suggesting its potential roles in the seed development.

Gene promoters are DNA sequences located upstream of gene coding regions and contain multiple *cis*-acting elements, which are specific binding sites for proteins involved in the initiation and regulation of transcription [38]. The promoters of *GmPK* were densely in transcription factors bidding sites, including MYB, MYC and WRKY, indicating that these transcription factors may be relevant to *GmPK* expression. It was reported that the *cis*-acting element W-box (TTGACC) was present on the promoter of PK gene *DkPK1* in persimmon. By using the yeast one-hybrid method, DkWRKY3 and DkWRKY15 were found to interact with the promoter of *DkPK1* [39]. In this study, 11 *GmPK* genes possess the W-box (Fig. 6; Table S4) in their promoters. These *GmPK* genes probably could be upregulated by WRKY genes in soybean. Further study could use the yeast one-hybrid system to verify this speculation.

92.6% of the *GmPK* gene promoters contained the salt-regulated element (SRE, GT1GMSCAM4) (Fig. 6). Therefore, we speculated that *GmPK* genes might play roles on the soybean salt tolerance. However, studies on the involvement of soybean *PK* genes in salt stress response have rarely been reported. Based on the qRT-PCR, 16 *GmPK* genes were found to be up-regulated by NaCl (Fig. 7). Previously, Huang [40] screened a population of soybean accessions using GWAS analysis and identified QTL associated with salt tolerance. Within these QTL regions, 10 candidate genes including the *PK* gene *GmPK6* have been identified. In this study, the expression of *GmPK6* was induced at 6 and 12 h after NaCl treatment, indicating that *GmPK6* might be a candidate gene responsible for the salt tolerance. Furthermore, we identified 6 *GmPK* genes were continuously regulated by salt and ABA. It is noteworthy that 4 of them belonged to the PKc subfamily, suggesting that PKc subfamily might play important roles in the salt tolerance regulation. *GmPK21*, which showed the most sensitive to NaCl was selected to further analysis by ectopic expressed in *Arabidopsis*. The result showed that the *GmPK21*-overexpression plants were more sensitive to the salt stress, suggesting that *GmPK21* might negatively regulate salt tolerance.

Notably, *GmPK21* is homologous to the rice *PK* gene *OsPK5* (LOC_Os04g58110) (Fig. 1). Zhu et al. reported that OsSAP6, a saline-alkaline tolerance regulator in rice could interacts with OsPK5. Furthermore, overexpression of *OsPK5* in rice improved soda saline-alkaline tolerance [21]. In our study, *GmPK21* is also involved in the salt stress tolerance regulation although it performed opposite function to its homologs in rice. This initial research on the function of *GmPK21* should be followed by further work that focuses on the soybean transformation, and then thoroughly explore its function on salt tolerance.

Conclusions

This study provided a comprehensive characterization of the soybean *PK* family genes, highlighting their structures, expression patterns and the potential function in salt tolerance. The results indicated that *GmPK* genes could respond to the NaCl treatment. *GmPK21*, which represented the most significant change under NaCl treatment was found to negatively regulate the salinity tolerance. This research could have significant implications for the development of genetic improvement strategies to increase soybean tolerance to salt, thus contributing to food security and agricultural sustainability.

Materials and methods

Genome-wide identification of *PK* genes in soybean

All of the genome sequences data of soybean cultivar Zhonghuang13 were downloaded from the Genome Warehouse (GWH) database in the BIG Data Center under Accession Number GWHAAEV00000000.1 [26]. The Hidden Markow Model (HMM) of PK and PK_C domain (PF00224 and PF02887) was retrieved from the Pfam database (<http://pfam.xfam.org>) [41], and then was used to search against the Zhonghuang13 genome. All of the putative proteins were extracted and confirmed by the Pfam and NCBI-CDD database (<https://www.ncbi.nlm.nih.gov/cdd>). The information of soybean PK proteins including molecular weights and isoelectric points were calculated using the online program ExPASy (<https://www.expasy.org>) [42].

Phylogenetic tree was constructed using MEGA 7.0 by the neighbor-joining method (<https://www.megasoftware.net>) [43]. Bootstrap analysis was carried out with 1000 replications. The tree file was edited using iTOL v5 (<https://itol.embl.de/>).

Chromosomal location and gene duplication analysis of soybean *PK* genes

The physical positions of soybean *PK* genes were extracted from the annotation file downloaded from GWH database. Then, the chromosomal location map

was drawn using the MapChart (v.2.32) software [44]. Potential gene duplications were determined by two major criteria: length of aligned sequence covers $\geq 75\%$ of longer gene and similarity of aligned regions is $\geq 75\%$. Ka and Ks values were calculated using KaKs Calculator (http://code.google.com/p/kaks-calculator/wiki/KaKs_Calculator) [45]. MCSscanX was used to detect the synteny of *PK* genes between soybean and other plants [46].

Gene structure and conserved motifs analysis

The gene structures of *GmPK* genes were retrieved from the GFF3 annotation file downloaded from GWH database and then visualized by the Gene Structure Display Server (<http://gsds.cbi.pku.edu.cn>). To identify the conserved motifs of *GmPK* proteins, the online program MEME (<http://meme-suite.org/tools/meme>) was used.

Expression analysis of soybean *PK* genes in different tissues

Soybean cultivar Zhonghuang13 was grown in a controlled culture room under short day condition (12 h light/12 h dark). The root, stem, leaf, shoot apical, cotyledon was sampled at 12 days after emergence (DAE), and the flower and pod were sampled at 34 DAE and 50 DAE, respectively. Each sample contained 3 whole roots from 3 independent plants. Three biological replicates were performed. The total RNA of these samples was extracted and reverse-transcribed for subsequent quantitative real-time PCR (qRT-PCR) analysis. Data were presented as means \pm SD, and Student's t-tests were used by SPSS statistics 19 to assess the significance of differences.

Cis-element analysis of *GmPK* genes

For the *cis*-element analysis, the 1500 bp upstream sequences of soybean *PK* family genes were obtained from the GWH database. The PLANTCARE database (<http://bioinformatics.psb.ugent.be/webtools/plantcare/html/>) was used to predict the *cis*-elements of the *GmPK* gene promoters.

Identification of soybean *PK* genes in response to the NaCl and ABA treatment

The seedlings of soybean cultivar Zhonghuang13 were grown in a controlled culture room at 25 °C with the photoperiod of 12 h light/12 h dark. For the NaCl and ABA treatment, 14-day-old seedlings were gently removed from the soil and cultivated in Hoagland liquid medium for 2 days. After that, the seedlings were transferred into new Hoagland liquid medium containing 200 mM NaCl or 100 μM ABA. The roots from control and treated seedlings were sampled at 0 h, 3 h, 6 h and 12 h after treatment and then immediately immersed in liquid nitrogen and stored at -80 °C for RNA extraction and qRT-PCR.

Each sample contained 3 whole roots from 3 independent plants. Three biological replicates were performed. Data were presented as means \pm SD, and Student's t-tests were used by SPSS statistics 19 to assess the significance of differences.

qRT-PCR analysis

The total RNA of the tested samples was extracted using Trizol reagent. qRT-PCR with 3 technical replicates for each of the triplicate biological samples was conducted to measure the expression levels of the *GmPK* genes. qRT-PCR was performed by using Roche 480 Light Cycler (Roche, Mannheim, Germany) and the Takara SYBR Premix ExTaq (Takara, Japan). Gene expression levels were then calculated according to the method ($2^{-\Delta\Delta CT}$) described by Livak and Schmittgen [47]. For the expression pattern of those 27 *GmPK* genes in different tissues and under NaCl treatment, *GmActin* (Glyma.18G290800) was used as the reference gene. For the expression level of *GmPK21* in the transgenic *Arabidopsis*, *AtActin2* (AT3G18780) was used as the reference gene. The details of the primers were shown in Table S5.

Histochemical GUS assays

The promoter of *GmPK21* was amplified by genomic PCR (The primers *GmPK21pro-F* and *GmPK21pro-R* were shown in Table S5) and then was inserted into the linearized DX2181 vector (digested by HindIII and BamHI) using the EasyGeno Assembly Cloning kit (Tiangen, VI201), generating the *GmPK21pro-GUS* fusion plasmid. The plasmid was then introduced into the *Agrobacterium tumefaciens* strain GV3101 and then transferred to *Arabidopsis* ecotype Columbia by using the floral dip method [48]. To detect GUS activity in different tissues of transgenic *Arabidopsis*, the seedlings, flowers and siliques were sampled and incubated in the X-Gluc solution for 16 h at 37 °C [49]. To detect the GUS activity after the NaCl treatment, the *Arabidopsis* seedlings were submerged in the 1/2 MS medium containing 100 mM NaCl. The roots of the *Arabidopsis* treated by NaCl were sampled after 6 h treatment, and the roots of the *Arabidopsis* which submerged in the 1/2 MS medium without NaCl were used as control. Then all of the samples were incubated in the X-Gluc solution for 16 h at 37 °C. In order to remove the chlorophyll, the samples were transferred into the ethanol (70% v/v) and then observed under stereomicroscope (Leica S9i, Germany). The samples were collected from 3 different transgenic *Arabidopsis* lines.

Subcellular localization of *GmPK21*

The CDS without the termination codon of *GmPK21* was amplified by PCR using the primer *GmPK21-F1* and *GmPK21-R1* (Table S5) and then was introduced

into the plasmid linearized pAN580 vector (digested by XbaI and BamHI) using the EasyGeno Assembly Cloning kit (Tiangen, VI201), generating the *GmPK21*-GFP fusion plasmid. The empty vector pAN580 was used as the control. The *GmPK21*-GFP and empty vector pAN580 were transformed into the *Arabidopsis* or tobacco protoplasts [50] respectively. The GFP signal was then analyzed using the LSM710 confocal microscope (Zeiss, Oberkochen, Germany).

Overexpression of *GmPK21* in *Arabidopsis*

The full length of the *GmPK21* CDS was amplified by PCR using the primer *GmPK21*-F2 and *GmPK21*-R2 (Table S5) and then was introduced into the linearized plasmid pC3300s (digested by SacI and BamHI) using the EasyGeno Assembly Cloning kit (Tiangen, VI201), generating the pC3300s-35S::*GmPK21*. The construct was then transformed into *Arabidopsis* (Col-0) using Agrobacterium GV3101. The seeds of transformants were selected by 1/2 MS medium containing glufosinate solution. The RT-PCR and qRT-PCR was then performed to confirm the presence of the *GmPK* gene in the glufosinate resistant lines (The RT-PCR primers RT-*GmPK21*-F/ RT-*GmPK21*-R and qRT-PCR primers q*GmPK21*-F (Ara)/q*GmPK21*-R(Ara) were shown in Table S5). The PK activity of 20-day-old transgenic *Arabidopsis* and WT was determined by using the Pyruvate Kinase (PK) Activity Assay Kit (BC0540, Solarbio life sciences). 3 biological replicates were performed and 10 seedlings (aboveground parts) were pooled per biological replicate. Data were presented as means \pm SD, and Student's t-tests were used by SPSS statistics 19 to assess the significance of differences.

Salt stress treatment of the *GmPK21* transgenic *Arabidopsis*

Three lines of the T3 transgenic *Arabidopsis* plants were used for NaCl treatment assay. The *Arabidopsis* were germinated in the 1/2 MS medium. The 3-day-old seedlings were then transferred to the new 1/2 MS medium containing 200 mM NaCl. The seedlings in the 1/2 MS without NaCl were used as control. 6 days later, the status of the plants was observed and the length of the primary roots were measured. At least 20 seedlings' roots were measured for each line. Data were presented as means \pm SD, and Student's t-tests were used by SPSS statistics 19 to assess the significance of differences.

Meanwhile, 3-day-old seedlings were transferred to the soil, and grown in an incubator (23°C) under short day condition (8 h light/16 h dark). 21 days later, seedlings were treated with 200 mM NaCl for 19 days. The status of the plants was observed and the fresh weight of aboveground parts of the seedlings were measured.

At least 20 seedlings' fresh weight were measured for each line. Data were presented as means \pm SD, and Student's t-tests were used by SPSS statistics 19 to assess the significance of differences. Then the aboveground parts of the *Arabidopsis* seedlings were used to measure the proline (Pro) and malondialdehyde (MDA) content. The content of Pro and MDA was determined by Proline (Pro) Content Assay Kit (Solarbio, BC0290) and Malondialdehyde (MDA) Content Assay Kit (Solarbio, BC0025) according to the kit instructions. 3 biological replicates were performed and 10 seedlings were pooled per biological replicate.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12864-023-09929-7>.

Additional file 1: Figure S1. Multiple sequence alignment of 27 GmPKs. The red and blue bars represent the PK domain and PK_C domain, respectively.

Additional file 2: Figure S2. The consensus sequences and their logos of the 10 conserved motifs predicted by MEME program.

Additional file 3: Figure S3. The subcellular localization of a *GmPK21*-GFP in tobacco protoplasts.

Additional file 4: Table S1. Sequences of PK genes in soybean, *Arabidopsis* and rice.

Additional file 5: Table S2. Segmental and tandem duplications of *GmPK* gene pairs in soybean and inference of duplication time.

Additional file 6: Table S3. Synteny analysis of PK genes between soybean and other organism (*Arabidopsis* and Rice).

Additional file 7: Table S4. *Cis*-regulatory element analysis in soybean PK genes.

Additional file 8: Table S5. Sequences of primers used in this study.

Authors' contributions

Lifeng Zhang and Wei Liu designed the research; Wei Liu, Yubin Wang, and Yanwei Zhang performed the experiment and analyzed the data; Caijie Wang and Ran Xu provided the plant material; Wei Liu and Lifeng Zhang prepared the original draft; Lifeng Zhang, Yubin Wang, Yanwei Zhang, Wei Li and Haiying Dai revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the grants from the National Natural Science Foundation of China (U22A20467 and 32301905); Natural Science Foundation of Shandong Province (ZR2020QC119); Agricultural Variety Improvement Project of Shandong Province (2021LZGC003), China Agriculture Research System (CARS-04-CES12) and Agricultural Scientific and Technological Innovation Project of Shandong Academy of Agricultural Sciences (CXGC2023A02). All of the genome sequences data of soybean cultivar Zhonghuang13 were downloaded from the Genome Warehouse (GWH) database in the BIG Data Center under Accession Number GWHAEV00000000.1

Availability of data and materials

All of the sequences data of soybean cultivar Zhonghuang13 were downloaded from the Genome Warehouse (GWH) database in the BIG Data Center under Accession Number GWHAEV00000000.1 (<https://ngdc.cncb.ac.cn/syomics/download>). The CDS and protein sequences of *GmPKs* were shown in Table S1. The protein sequences of PK genes in *Arabidopsis* and rice were obtained from the database Phytozome (<https://phytozome-next.jgi.doe.gov/>) and were shown in Table S1.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that this study does not have any potential conflicts of interest.

Received: 18 August 2023 Accepted: 19 December 2023

Published online: 22 January 2024

References

- Fernie AR, Carrari F, Sweetlove LJ. Respiratory metabolism: glycolysis, the TCA cycle and mitochondrial electron transport. *Curr Opin Plant Biol.* 2004;7(3):254–61.
- Lichtenthaler HK. The 1-Deoxy-D-Xylulose-5-phosphate pathway of isoprenoid biosynthesis in plants. *Annu Rev Plant Biol.* 1999;50(1):47–65.
- Ambast PK, Kayastha AM. Plant pyruvate kinase. *Biol Plantarum.* 2002;45:1–10.
- Hu Z, Plaxton WC. Purification and characterization of cytosolic pyruvate kinase from leaves of the castor oil plant. *Arch Biochem Biophys.* 1996;333(1):298–307.
- Plaxton WC. Molecular and immunological characterization of plastid and cytosolic pyruvate kinase isozymes from castor-oil-plant endosperm and leaf. *Eur J Biochem.* 1989;181(2):1443–51.
- Schuller KA, Turpin DH, Plaxton WC. Metabolite regulation of partially purified soybean nodule phosphoenolpyruvate carboxylase. *Plant Physiol.* 1990;94(3):1429–35.
- Plaxton WC, Smith CR, Knowles VL. Molecular and regulatory properties of leucoplast pyruvate kinase from *Brassica napus* (rapeseed) suspension cells. *Arch Biochem Biophys.* 2002;400(1):54–62.
- Andre C, Froehlich JE, Moll MR, Benning C. A heteromeric plastidic pyruvate kinase complex involved in seed oil biosynthesis in *Arabidopsis*. *Plant Cell.* 2007;19(6):2006–22.
- Baud S, Wuilleme S, Dubreucq B, De Almeida A, Vuagnat C, Lepiniec L, Miquel M, Rochat C. Function of plastidial pyruvate kinases in seeds of *Arabidopsis thaliana*. *Plant J.* 2007;52(3):405–19.
- Knowles VL, McHugh SG, Hu Z, Dennis DT, Miki BL, Plaxton WC. Altered growth of transgenic tobacco lacking leaf cytosolic pyruvate kinase. *Plant Physiol.* 1998;116(1):45–51.
- Zhang B, Liu JY. Cotton cytosolic pyruvate kinase GhPK6 participates in fast fiber elongation regulation in a ROS-mediated manner. *Planta.* 2016;244:915–26.
- Zhang Y, Xiao W, Luo L, Pang J, Rong W, He C. Downregulation of OsPK1, a cytosolic pyruvate kinase, by T-DNA insertion causes dwarfism and panicle enclosure in rice. *Planta.* 2012;235:25–38.
- Yang B, Chen M, Zhan C, Liu K, Cheng Y, Xie T, Zhu P, He Y, Zeng P, Tang H, Tsugama D, Chen S, Zhang H, Cheng J. Identification of OsPK5 involved in rice glycolytic metabolism and GA/ABA balance for improving seed germination via genome-wide association study. *J Exp Bot.* 2022;73(11):3446–61.
- Cai Y, Li S, Jiao G, Sheng Z, Wu Y, Shao G, Xie L, Peng C, Xu J, Tang S, Wei X, Hu P. OsPK2 encodes a plastidic pyruvate kinase involved in rice endosperm starch synthesis, compound granule formation and grain filling. *Plant Biotechnol J.* 2018;16(11):1878–91.
- Cai Y, Zhang WW, Jin J, Yang XM, You XM, Yan HG, Wang L, Chen J, Xu JH, Chen WW, Chen XG, Ma J, Tang XJ, Kong F, Zhu XP, Wang GX, Jiang L, Terzaghi W, Wang CM, Wan JM. OsPKpa1 encodes a plastidic pyruvate kinase that affects starch biosynthesis in the rice endosperm. *J Integr Plant Biol.* 2018;60(11):1097–118.
- Hu L, Tu B, Yang W, Yuan H, Li JL, Guo LA, Zheng L, Chen WL, Zhu XB, Wang YP, Qin P, Ma BT, Li SG. Mitochondria-associated pyruvate kinase complexes regulate grain filling in rice. *Plant Physiol.* 2020;183(3):1073–87.
- Luo L, Wan Q, Zhang K, Zhang X, Guo R, Wang C, Zheng C, Liu F, Ding Z, Wan Y. AhAB1/s negatively regulate salt-stress response in Peanut. *Front Plant Sci.* 2021;12:741641.
- Khan MN, Sakata K, Komatsu S. Proteomic analysis of soybean hypocotyl during recovery after flooding stress. *J Proteomics.* 2015;121:15–27.
- Kim KJ, Park CJ, Ham BK, Choi SB, Lee BJ, Paek K. Induction of a cytosolic pyruvate kinase 1 gene during the resistance response to *Tobacco mosaic virus* in *Capsicum annuum*. *Plant Cell Rep.* 2006;25:59–364.
- Yu L, Dai Z, Zhang Y, Iqbal S, Lu S, Guo L, Yao X. Proteome wide identification of S-sulfenylation cysteines reveals metabolic response to freezing stress after cold acclimation in *Brassica napus*. *Front Plant Sci.* 2022;13:1014295.
- Zhu F, Wang K, Li D, Liu Z, Li M, Wang Z, Li X, Lan X, Guan Q. OsSAP6 positively regulates soda saline-alkaline stress tolerance in rice. *Rice.* 2022;15(1):69.
- Wilcox JR. World distribution and trade of soybean. In: Soybeans: improvement, production, and uses, agronomy monographs; Boerma HG, Specht JE, Eds. Madison: American Society of Agronomy, 2004;16. pp. 1–14.
- Rasheed A, Raza A, Jie H, Mahmood A, Ma Y, Zhao L, Xing H, Li L, Hassan MU, Qari SH, Jie Y. Molecular tools and their applications in developing salt-tolerant soybean (*Glycine max* L.) cultivars. *Bioengineering.* 2022;9(10):495.
- Wulfert S, Schilasky S, Krueger S. Transcriptional and biochemical characterization of cytosolic pyruvate kinases in *Arabidopsis thaliana*. *Plants (Basel).* 2020;9(3):353.
- Dong N, Chen L, Ahmad S, Cai Y, Duan Y, Li X, Liu Y, Jiao G, Xie L, Hu S, Sheng Z, Shao G, Wang L, Tang S, Wei X, Hu P. Genome-wide analysis and functional characterization of pyruvate kinase (PK) gene family modulating rice yield and quality. *Int J Mol Sci.* 2022;23(23):15357.
- Shen Y, Du H, Liu Y, Ni L, Wang Z, Liang C, Tian Z. Update soybean Zhonghuang 13 genome to a golden reference. *Sci China Life Sci.* 2019;62:1257–60.
- Kong H, Landherr LL, Frohlich MW, Leebens-Mack J, Ma H, DePamphilis CW. Patterns of gene duplication in the plant *SKP1* gene family in angiosperms: evidence for multiple mechanisms of rapid gene birth. *Plant J.* 2007;50(5):873–85.
- Ashraf M, Foolad MR. Roles of glycine betaine and proline in improving plant abiotic stress resistance. *Environ Exp Bot.* 2007;59:206–16.
- Oliver SN, Lunn JE, Urbanczyk-Wochniak E, Lytovchenko A, van Dongen JT, Faix B, Schmalzljin E, Fernie AR, Geigenberger P. Decreased expression of cytosolic pyruvate kinase in potato tubers leads to a decline in pyruvate resulting in an *in vivo* repression of the alternative oxidase. *Plant Physiol.* 2008;148:1640–54.
- Shan Z, Luo X, Wu M, Wei L, Fan Z, Zhu Y. Genome-wide identification and expression of GRAS gene family members in cassava. *BMC Plant Biol.* 2020;20(1):1–16.
- Moore RC, Purugganan MD. The early stages of duplicate gene evolution. *Proc Natl Acad Sci U S A.* 2003;100(26):15682–7.
- Schmutz J, Cannon SB, Schlueter J, Ma JX, Mitros T, Nelson W, Hyten D, Song Q, Thelen J, Cheng J, Xu D, Hellsten U, May GD, Yu Y, Sakura T, Umezawa T, Bhattacharyya MK, Sandhu D, Valliyodan B, Lindquist E, Peto M, Grant D, Shu S, Goodstein D, Barry K, Futrell-Griggs M, Abernathy B, Du J, Tian Z, Zhu L, Gil LN, Joshi T, Libault M, Sethuraman A, Zhang X, Shinozaki K, Nguyen HT, Wing RA, Cregan P, Specht J, Grimwood J, Rokhsar D, Stacey G, Shoemaker RC, Jackson SA. Genome sequence of the palaeopolyploid soybean. *Nature.* 2010;463(7278):178–83.
- Flagel LE, Wendel JF. Gene duplication and evolutionary novelty in plants. *New Phytol.* 2009;183(3):557–64.
- Cusack BP, Wolfe KH. When gene marriages don't work out: divorce by subfunctionalization. *Trends Genet.* 2007;23(6):270–2.
- Blanc G, Wolfe KH. Functional divergence of duplicated genes formed by polyploidy during *Arabidopsis* evolution. *Plant Cell.* 2004;16(7):1679–91.
- Roulin A, Auer PL, Libault M, Schlueter J, Farmer A, May G, Stacey G, Doerge RW, Jackson SA. The fate of duplicated genes in a polyploid plant genome. *Plant J.* 2013;73(1):143–53.
- Andre C, Benning C. *Arabidopsis* seedlings deficient in a plastidic pyruvate kinase are unable to utilize seed storage compounds for germination and establishment. *Plant Physiol.* 2007;145(4):1670–80.

38. Hernandez-Garcia CM, Finer JJ. Identification and validation of promoters and *cis*-acting regulatory elements. *Plant Sci.* 2014;217:109–19.
39. Guan C, Wang M, Zhang Y, Ruan X, Zhang Q, Luo Z, Yang Y. DkWRKY interacts with pyruvate kinase gene DkPK1 and promotes natural deastringency in C-PCNA persimmon. *Plant Sci.* 2020;290:110285.
40. Huang L. Genome-Wide association mapping identifies QTLs and candidate genes for salt tolerance in soybean. Master's Thesis, University of Arkansas, Fayetteville, AR, USA, 2013.
41. Finn RD, Coggill P, Eberhardt RY, Eddy SR, Mistry J, Mitchell AL, Potter SC, Punta M, Qureshi M, Sangrador-Vegas A, Salazar GA, Tate J, Salazar GA. The Pfam protein families database: towards a more sustainable future. *Nucleic Acids Res.* 2015;44:D279–85.
42. Artimo P, Jonnalagedda M, Arnold K, Baratin D, Csardi G, Castro E, Duvaud S, Flegel V, Fortier A, Gasteiger E, Grosdidier A, Hernandez C, Ioannidis V, Kuznetsov D, Liechti R, Moretti S, Mostaguir V, Redaschi N, Rossier G, Xenarios I, Stockinger H. ExPASy: SIB bioinformatics resource portal. *Nucleic Acids Res.* 2012;40:W597–603.
43. Kumar S, Stecher G, Tamura K. MEGA7: molecular evolutionary genetics analysis version 7.0 for bigger datasets. *Mol Biol Evol.* 2012;33(7):1870–4.
44. Voorrips RE. MapChart: software for the graphical presentation of linkage maps and QTLs. *J Hered.* 2002;93(1):77–8.
45. Zhang Z, Li J, Zhao X, Wang J, Wong GKS, Yu J. KaKs_Calculator: calculating Ka and Ks through model selection and model averaging. *Genom Proteom Bioinf.* 2006;4:259–63.
46. Wang Y, Tang H, DeBarry JD, Tan X, Li J, Wang X, Lee TH, Jin H, Marler B, Guo H, Kissinger JC, Paterson AH. MCScanX: a toolkit for detection and evolutionary analysis of gene synteny and collinearity. *Nucleic Acids Res.* 2012;40(7):e49.
47. Livak KJ, Schmittgen TD. Analysis of relative gene expression data using real-time quantitative PCR and the $2^{-\Delta\Delta CT}$ method. *Methods.* 2001;25(4):402–8.
48. Clough SJ, Bent AF. Floral dip: a simplified method for agrobacterium mediated transformation of *A. thaliana*. *Plant J.* 1998;16(6):735–43.
49. Jefferson RA. The GUS reporter gene system. *Nature.* 1989;342(6251):837–8.
50. Yoo SD, Cho YH, Sheen J. Arabidopsis mesophyll protoplasts: a versatile cell system for transient gene expression analysis. *Nat Protoc.* 2007;2(7):1565–72.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Ready to submit your research? Choose BMC and benefit from:

- fast, convenient online submission
- thorough peer review by experienced researchers in your field
- rapid publication on acceptance
- support for research data, including large and complex data types
- gold Open Access which fosters wider collaboration and increased citations
- maximum visibility for your research: over 100M website views per year

At BMC, research is always in progress.

Learn more biomedcentral.com/submissions

