Research Article
Cloning and Functional Determination of Ammonium Transporter PpeAMT3;4 in Peach

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Ammonium (NH₄⁺) plays key roles in plant growth, development, fruit quality, and yield. In plants, NH₄⁺ uptake and transport are facilitated by NH₄⁺ transporters (AMT). However, molecular mechanisms and physiological functions of type-II AMT (AMT2) transporters in fruit trees are still unclear, especially in peach. In this study, we cloned and characterized an AMT2 family gene from peach, PpeAMT3;4, and determined its function in yeast mutant. Expression analysis showed that PpeAMT3;4 was majorly expressed in peach roots and significantly decreased by NH₄⁺ excess but had no response to NH₄⁺ deficiency. Functional determination and ¹⁵nitrogen-labeled NH₄⁺ uptake assay in yeast cells implied that PpeAMT3;4 was a typical high-affinity transporter, with a \( K_m \) value of 86.3 \( \mu M \), that can uptake external NH₄⁺ in yeast cells. This study provides gene resources to uncover the biological function of AMT2 transporters and reveals molecular basis for NH₄⁺ uptake and nitrogen (N) nutrition mechanisms in fruit trees.

1. Introduction

Ammonium (NH₄⁺) is the preferred form of nitrogen (N) source absorbed by both annual and perennial plant species, especially in N-deficient soils [1, 2]. However, with the increasing soil N input and atmospheric deposition, plants have to deal with NH₄⁺ stress from sources below and above the ground [1–6]. Thus, an optimal amount of NH₄⁺ should be effectively absorbed from the soil via plant roots, to sustain basic growth demands.

Extensive studies in angiosperms [3–5] and in basal land plant liverwort [6] indicated that NH₄⁺ acquisition and uptake were performed by NH₄⁺ transporters (AMT) through the plasma membrane of root cells. The first plant AMT family gene was observed in Arabidopsis [7], and AtAMT1;1, AtAMT1;2, and AtAMT1;3 successfully restored the normal growth of the yeast mutant that is deficient in NH₄⁺ uptake systems. Subsequent studies of AMT transporters have been identified in diverse plant species, including Lotus japonicus (L. japonicus) [8, 9], Lycopersicon esculentum (L. esculentum) [10–12], Populus trichocarpa (P. trichocarpa) [13], Oryza sativa (O. sativa) [14, 15], Triticum aestivum (T. aestivum) [16], Alternanthera philoxeroides (A. philoxeroides) [17], and so on, which have been characterized in Xenopus oocytes or yeast mutant. The AMT family transporters can be divided into two subfamilies: AMT1 and AMT2 [3–5]. In particular, the phosphorylation of amino acid residues of AMT proteins is a recognized means, by which NH₄⁺ uptake activities were regulated [18, 19]. In Arabidopsis, the phosphorylation of the threonine (Thr) residue in the C-terminal tail region of AtAMT1.1 (Thr^460), AtAMT1.2 (Thr^472), and AtAMT1.3

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Extensive studies in angiosperms [3–5] and in basal land plant liverwort [6] indicated that NH₄⁺ acquisition and uptake were performed by NH₄⁺ transporters (AMT) through the plasma membrane of root cells. The first plant AMT family gene was observed in Arabidopsis [7], and AtAMT1;1, AtAMT1;2, and AtAMT1;3 successfully restored the normal growth of the yeast mutant that is deficient in NH₄⁺ uptake systems. Subsequent studies of AMT transporters have been identified in diverse plant species, including Lotus japonicus (L. japonicus) [8, 9], Lycopersicon esculentum (L. esculentum) [10–12], Populus trichocarpa (P. trichocarpa) [13], Oryza sativa (O. sativa) [14, 15], Triticum aestivum (T. aestivum) [16], Alternanthera philoxeroides (A. philoxeroides) [17], and so on, which have been characterized in Xenopus oocytes or yeast mutant. The AMT family transporters can be divided into two subfamilies: AMT1 and AMT2 [3–5]. In particular, the phosphorylation of amino acid residues of AMT proteins is a recognized means, by which NH₄⁺ uptake activities were regulated [18, 19]. In Arabidopsis, the phosphorylation of the threonine (Thr) residue in the C-terminal tail region of AtAMT1.1 (Thr^460), AtAMT1.2 (Thr^472), and AtAMT1.3
(Thr\textsuperscript{464}) led to the loss of NH\textsubscript{4}\textsuperscript{+} transport activity in response to increasing external NH\textsubscript{4}\textsuperscript{+} supplies [18–21], providing a novel regulatory mechanism that NH\textsubscript{4}\textsuperscript{+} transport can be rapidly shut-off under high NH\textsubscript{4}\textsuperscript{+} supply conditions.

Functional studies of plant AMT members were mainly focused on the AMT1 family, especially of annual model plants. However, molecular mechanisms towards NH\textsubscript{4}\textsuperscript{+} uptake and transport in fruit trees are largely rare but were just observed in citrus [22] and pear [23, 24]. The biological and physiological functions of AMT2 members remain unknown. Favorably, the knowledge on NH\textsubscript{4}\textsuperscript{+} uptake and transport in model plants provides valuable insights into the investigation of their roles in fruit trees.

As one of the most popular Rosaceae fruit crops, peach (\textit{Prunus persica}) has its genome sequenced [25, 26]. In this study, we isolated and characterized a putative AMT2 family gene from peach (entitled as PpeAMT3;4) and determined that PpeAMT3;4 is a typical HATS-mediated AMT member responsible for NH\textsubscript{4}\textsuperscript{+} uptake in peach roots. Nonetheless, our findings provide a molecular basis of NH\textsubscript{4}\textsuperscript{+} uptake for fruit trees.

2. Materials and Methods

2.1. Plant Material and Growth Condition. 'Feicheng' peach seedlings grown in the Key Laboratory of Molecular Module-Based Breeding of High Yield and Abiotic Resistant Plants in Universities of Shandong in Yantai, China, were used throughout this study. Germinated seedlings with similar growth status were transferred into 1/2 Murashige and Skoog (MS) liquid solution ([17, 27], containing approximately 1 mM NH\textsubscript{4}Cl), cultivated in a climate-controlled growth cabinet that was maintained under 28°C/23°C and 12/12 h light/dark, with 60% relative humidity.

For the NH\textsubscript{4}\textsuperscript{+} deficiency treatments, NH\textsubscript{4}\textsuperscript{+} was omitted from the 1/2 MS medium. For the NH\textsubscript{4}\textsuperscript{+} excess treatments, germinated seedlings were grown in 1/2 MS solution containing 20 mM NH\textsubscript{4}Cl (pH 5.8). Seedlings were exposed to treatment for 72 h before quantitative real-time PCR (qRT-PCR) determination.

2.2. Cloning of PpeAMT3;4 Gene in Peach. Protein sequences of poplar AMT genes [13] were used as query to BLAST the Phytomeze Peach Genome Database (http://www.phytomeze.net) to identify putative homologues in peach. Information of PpeAMT genes were listed in Supplemental Table 1. Coding sequence (CDS) of the PpeAMT3;4 gene was downloaded from the database, and the first 18 bp sequence from the ATG codon and the last 19 bp sequence from the TAA codon were chosen as the forward primer and reverse primer, respectively (Table 1). Total RNA of 'Feicheng' peach seedling was extracted using MiniBEST Plant RNA Extraction Kit (TaKaRa, Dalian, China) and reverse transcribed into the 1st cDNA using PrimeScript\textsuperscript{™} RT reagent Kit (TaKaRa, Dalian, China). Normal gene amplification was carried out to obtain the CDS region of PpeAMT3;4 and then sequenced in Sanon Biotech (Shanghai, China).

2.3. Phylogenetic Analysis of PpeAMT Genes in Peach. Full-length amino acid sequences of PpeAMT transporters were aligned by ClustalX2.1 and imported into the Molecular Evolutionary Genetics Analysis (MEGA) package version 4.1. Phylogenetic analyses were conducted according to the description of Liang et al. [28]. Branch lengths indicate the corresponding phylogenetic distances. Sequence logos of AMT1 and AMT2 subfamilies were shown on the right, generated using WEBLOGO (http://weblogo.berkeley.edu/logo.cgi). The grand average of hydropathicity (GRAVY) and aliphatic index analyses of PpeAMT3;4 were calculated using the ProtParam tool (http://web.expasy.org/protparam/), as described by Liang et al. [28].

2.4. qRT-PCR Assays. Specific expression primers for PpeAMT3;4 and Ubiquitin (control gene) were designed using the NCBI/Primer-BLAST online server. Primer sequences were listed in Table 1. According to the description of Liang et al. [28], qRT-PCR analyses were carried out on 7500 Real-Time PCR System (Applied Biosystems, New York, USA), using SYBR Premix Ex Taq reaction kit (TaKaRa, Dalian, China). To calculate RT-qPCR efficiency and the starting template concentration for each sample, the linear regression of the log (fluorescence) per cycle number data was used according to the description of Gazzarrini et al. [29]. The relative expression levels were presented after normalization to the internal control Ubiquitin from three independent biological repeats.

2.5. Functional Determination of PpeAMT3;4 in Yeast Mutant 31019b. The recombinant plasmid pYES2-AMT3;4 was constructed by cloning the CDS region of the PpeAMT3;4 gene into the pYES2 expression vector [17], using the primer pairs (Table 1, Kpn I site was introduced and underlined in the forward primer, Not I site was introduced and underlined in the reverse primer). The yeast strain 31019b (MATA mepL\textsuperscript{△} mep2C\textsuperscript{△}:LEU2 mep3C\textsuperscript{△}:KanMX2 ura3, [7, 13, 17]) was transformed with pYES2 harboring the CDS of PpeAMT3;4. Yeast complementation tests were carried out as described in previous reports [7, 13, 17]. Yeast strain 31019b was transformed with pYES2 or pYES2-AMT3;4, respectively. The growth of yeast cells were determined in the yeast nitrogen base (YNB) liquid medium, supplemented with 0.02, 0.2, or 2 mM NH\textsubscript{4}\textsuperscript{+} as the sole N source (pH 5.8). Pictures were taken at the 3rd day after incubation at 30°C. The growth of transformed yeast cells in the YNB liquid medium was checked by determining absorbance at 600 nm [29].

2.6. \textsuperscript{15}N Uptake Kinetics Assay. \textsuperscript{15}N labeled NH\textsubscript{4}\textsuperscript{+} uptake assays were carried out according to the description of Guo et al. [17]. Yeast cells transformed with pYES2-AMT3;4 or pYES2 were grown in the YNB liquid medium, supplemented with \textsuperscript{15}N labeled NH\textsubscript{4}Cl for 10 min. NH\textsubscript{4}\textsuperscript{+} content was determined by Flash-2000 Delta VADVADTAGE Mass Spectrometer (Thermo Fisher, Waltham, Massachusetts, USA). Michaelis-Menten kinetic constants (\(K_m\) and \(V_{max}\)) were calculated as described by Guo et al. [17].

2.7. Statistical Analysis. All data were statistically analyzed using independent samples' t-test in SPSS 13.0 software.
Table 1: Primer sequences used in this work.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Primer (5′-3′)</th>
<th>Amplicon (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amplication of PpeAMT3;4 CDS</strong></td>
<td>F: ATGATGCGAGGTTGGTG</td>
<td>1065</td>
</tr>
<tr>
<td></td>
<td>R: TTAGACCCACCTGAGTGGGA</td>
<td></td>
</tr>
<tr>
<td><strong>Specific expression primers of PpeAMT3;4</strong></td>
<td>F: TGTCCGAGGTTTACCGTTT</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td>R: TGAACCTGCCCCACATCCCATC</td>
<td></td>
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<tr>
<td><strong>Specific expression primers of Ubiquitin</strong></td>
<td>F: AGGCTAAGATCCAAGCA</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>R: CCACGAAGACGAAGCCTAAG</td>
<td></td>
</tr>
<tr>
<td><strong>Construction of pYES2-AMT3;4 plasmid</strong></td>
<td>F: GAGGCGGTACCATGATGCGAGTGGTG</td>
<td>1065</td>
</tr>
<tr>
<td></td>
<td>R: GCGAGGCGCCGCTTTAGCACCACCGTGGC</td>
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Figure 1: Amino acid sequence alignment of PpeAMT proteins in peach. Multiple sequence alignment of PpeAMT proteins were carried out via ClustalX2.1 software.
(SPSS Chicago, Illinois, USA). Details are described in figure legends. Asterisks indicate statistical differences between plants under control and stress treatment (*P < 0.05, **P < 0.01).

3. Results

3.1. Characteristics and Phylogenetic Tree Construction of PpAMT Transporters in Peach. By BLAST searching of the Phytozome Peach Genome Database, 14 putative PpAMT genes were screened and identified [27]. Pr70eain domain verification analyses showed that all PpAMT transporters contain the NH$_4^+$ transporter transmembrane domain (PF00909). Information of these PpAMT genes, including gene ID, gene location, CDS (coding sequence) length, and peptide length, are listed in Supplemental Table 1. Notably, the amino acid sequences of PpAMT proteins shared an overall identity of 51.09% (Figure 1). To confirm the evolutionary relationships of PpAMT proteins, a maximum likelihood (ML) phylogenetic tree was generated based on the alignment of the amino acid sequences of PpAMT proteins. All peach AMT transporters were classified into 2 major subgroups: AMT1 and AMT2 (Figure 2), each with 5 and 9 members, respectively. The AMT2 subgroup in peach was further divided into three subclades, including PpAMT2 (1 member), PpAMT3 (5 members), and PpAMT4 (3 members) (Figure 2).

3.2. Cloning and Expression Analysis of PpAMT3;4. As a member of the AMT2 subgroup in peach, the nucleotide sequence of PpAMT3;4 CDS was amplified from 'Feicheng' peach seedlings, using the specific primer pairs and the 1st cDNA template. According to the sequencing results, PpAMT3;4 possessed a coding sequence of 1065 bp, encoding a polypeptide of 355 amino acids with the deduced theoretical PI value of 8.55. Moreover, both the GRAVY and aliphatic index analysis indicated that PpAMT3;4 was a hydrophilic protein.

3.3. Expression Profiles of PpAMT3;4. We further performed reverse-transcribed PCR to determine the expression profiles of PpAMT3;4 in different tissues of 7-year-old 'Feicheng' trees. Results showed that PpAMT3;4 was majorly expressed in roots, followed by leaves, and hardly observed in stems, flowers, and fruits (Figure 3).

To investigate the role of PpAMT3;4 in maintaining NH$_4^+$ homeostasis in peach, we analyzed the expression profiles of PpAMT3;4 via the qRT-PCR analysis. Results showed that the expression of PpAMT3;4 was significantly decreased by NH$_4^+$ excess in roots of 'Feicheng' seedlings but had no response to NH$_4^+$ deficiency (Figure 4).

3.4. Functional Determination of PpAMT1;1 in Yeast Mutant. We further carried out functional determination of PpAMT3;4 via complementation of the yeast mutant 31019b [6, 13, 17, 30]. Results showed that yeast cells harboring pYES2 or pYES2-PpAMT3;4 grew well, with similar growth status, on the YNB medium that contains 2 mM Arg as the sole N source (Figure 5). Yeast cells harboring pYES2-PpAMT3;4 grew normally on the YNB medium supplemented under 0.2 and 2 mM NH$_4$Cl (Figure 5). These findings imply that PpAMT3;4 is involved in NH$_4^+$ uptake in peach roots.

3.5. $^{15}$N Uptake Kinetics Assay of ApAMT3;4 in Yeast Cells. To verify the proposition that PpAMT3;4 really functions as an active NH$_4^+$ transporter, we determined its NH$_4^+$ uptake activity and the exact amount of $^{15}$N-labeled NH$_4^+$ uptake in yeast cells via the $^{15}$N isotope labeling method. Yeast cells were grown in the NYB liquid medium labeled with $^{15}$N-labeled NH$_4$Cl, ranging from 0.02 mM to 2 mM. Affinity constant analysis showed that PpAMT3;4 exhibited a K$_m$ value of 86.3 µM and a t$_{max}$ value of 3.69 µmol·min$^{-1}$·µg$^{-1}$, respectively (Figure 6). These findings indicate that PpAMT3;4 was primarily involved in HATS-mediated NH$_4^+$ uptake in peach roots.

4. Discussion

NH$_4^+$ is the preferred form of N transport for lower energetic cost in assimilation [3--5, 29], while excess NH$_4^+$ is toxic to plant growth and development [30, 31]. In higher plants,
high-affinity AMT1 subgroup genes encode NH$_4^+$ transporters with a $K_m$ value of micromolar grade involved in the HATS for NH$_4^+$ uptake [12]. However, the molecular mechanism towards the AMT2 subgroup genes is largely rare. In this present study, we initially isolated and determined a high-affinity AMT2 subgroup transporter gene in...
peach, which helps to investigate the biological role of AMT2 family transporters in fruit trees.

Transcript levels of AMT1 genes are closely related to the N nutrition status of the plant, and NH$_4^+$ starvation mainly induced the expression levels of most AMT1 genes, may it be a clue of ‘starvation response’ for plants to grow under suboptimal N-source conditions [3, 16, 22]. However, PpAMT3;4 was mainly expressed in roots and was nonresponsive to NH$_4^+$ starvation in peach roots in this study but reduced significantly by excessive NH$_4^+$ stress (Figures 3 and 4). These findings implies that PpAMT3;4 may be an active NH$_4^+$ transporter at normal NH$_4^+$ supplies, even at extremely low NH$_4^+$ conditions, which is an indispensable AMT2 transporter responsible for NH$_4^+$ uptake in peach roots. If the NH$_4^+$ supply reached an excessive state, PpAMT3;4 began to stop its NH$_4^+$ uptake and transport capacity that are sufficient enough for internal N metabolism and usage.

Heterologous expression studies using NH$_4^+$ uptake defective yeast mutant or Xenopus oocytes indicate that AMT1 family genes encode high-affinity transporters [3, 4, 15], which play key roles in high-affinity NH$_4^+$ uptake from soils via the roots. While molecular mechanisms or biological functions of AMT2 subgroup members are extremely rare, in this present study, PpAMT3;4 could utilize the external NH$_4^+$ in yeast cells (Figure 5), and $^{15}$N labeled NH$_4^+$ uptake kinetics analysis exhibited a $K_m$ value of 86.3 μM (Figure 6). Nonetheless, PpAMT3;4 is a functional AMT2 transporter responsible for NH$_4^+$ uptake in peach roots, especially under normal and low external NH$_4^+$ conditions.

5. Conclusions

In this study, we isolated and characterized PpAMT3;4, an AMT2 family gene from peach, and determined its function in yeast mutant. The PpAMT3;4 gene was majorly expressed in peach roots, whose expression was decreased under NH$_4^+$ excess but had no response to NH$_4^+$ deficiency. Functional determination and $^{15}$N-labeled NH$_4^+$ uptake kinetics assay in yeast cells indicate that PpAMT3;4 was a typical high-affinity transporter, with a $K_m$ value of 86.3 μM and a $I_{max}$ value of 3.69 μmol min$^{-1}$ μg$^{-1}$, which can uptake external NH$_4^+$ in yeast cells. Nonetheless, PpAMT3;4 might be a NH$_4^+$ transporter involved in NH$_4^+$ uptake in peach roots. This study not only provides a technological system to uncover the biological function of AMT2 transporters in fruit trees but also reveals molecular basis for NH$_4^+$ uptake and N nutrition mechanisms.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

We declare that we do not have any commercial or associational interest that represents a conflict of interest with the work submitted.

Authors’ Contributions

Shuanghong You, Yuqing Wang, and Yanju Li contributed equally to this work.

Acknowledgments

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Supplementary Materials

Supplemental Table 1: information of PpAMT family genes in peach. (Supplementary Materials)

References


