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Unique features of the m⁶A methylome in *Arabidopsis thaliana*

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Recent discoveries of reversible N⁶-methyladenosine (m⁶A) methylation on messenger RNA (mRNA) and mapping of m⁶A methylomes in mammals and yeast have revealed potential regulatory functions of this RNA modification. In plants, defects in m⁶A methyltransferase cause an embryo-lethal phenotype, suggesting a critical role of m⁶A in plant development. Here, we profile m⁶A transcriptome-wide in two accessions of *Arabidopsis thaliana* and reveal that m⁶A is a highly conserved modification of mRNA in plants. Distinct from mammals, m⁶A in *A. thaliana* is enriched not only around the stop codon and within 3'-untranslated regions, but also around the start codon. Gene ontology analysis indicates that the unique distribution pattern of m⁶A in *A. thaliana* is associated with plant-specific pathways involving the chloroplast. We also discover a positive correlation between m⁶A deposition and mRNA abundance, suggesting a regulatory role of m⁶A in plant gene expression.

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N⁶-methyladenosine (m⁶A) is the most prevalent internal messenger RNA (mRNA) modification^{1–3} in eukaryotes including mammals⁴, plants^{5,6}, *Drosophila*⁷ and yeast⁸, as well as viruses with a nuclear phase⁹. This modification is installed by N⁶-adenosine methyltransferase. A 70 kDa SAM (S-adenosylmethionine)-binding subunit methyltransferase-like 3 (METTL3, also called MT-A70) was identified as one component of a methyltransferase complex in mammalian cells¹⁰. Recent studies have characterized this complex, which consists of METTL3, methyltransferase-like 14 (METTL14) and Wilms tumor 1-associated protein (WTAP)^{11–13}. METTL14 and METTL3 are two active methyltransferases that form a heterodimer to catalyze m⁶A RNA methylation, while WTAP interacts with this complex and substantially affects the mRNA methylation inside cells but not *in vitro*¹¹. Knockdowns of these methyltransferases affect mouse embryonic stem cell differentiation¹². Since 2011, two m⁶A RNA demethylases of FTO and ALKBH5 have been discovered; these demethylases are involved in mammalian development, RNA metabolism and fertility^{14,15}. These findings reveal the first examples of reversible RNA modification and indicate regulatory functions of reversible m⁶A methylation on mRNA and certain non-coding RNAs that contain m⁶A¹⁶. Subsequent profiling of m⁶A distributions in mammalian transcriptomes^{17,18} and the recent mapping of the yeast m⁶A methylome in the meiotic state¹⁹ further confirm the dynamic nature of m⁶A modification. These studies revealed that m⁶A is enriched around the stop codon and at 3'-untranslated regions (UTRs), as well as in long internal exons and at the transcription start site^{17–19}. Cellular proteins have also been found to preferentially bind m⁶A-containing RNA^{17,20}. The human YTH domain family 2 (YTHDF2) has recently been characterized to specifically recognize m⁶A-methylated mRNA and accelerate the decay of the bound mRNA²⁰.

In *Arabidopsis thaliana*, the m⁶A content in mRNA varies across tissues with a high ratio of m⁶A/A found in flower buds⁶. This variation correlates with the expression levels of the plant methyltransferase MTA (the plant homologue of human METTL3, encoded by *At4g10760*)⁶. Previous studies have also shown that m⁶A predominantly locates at the 3' end of transcripts in a region 100–150 bp before the poly(A) tail in *A. thaliana* mRNA²¹. Inactivation of *MTA* prevents the progression of the developing embryo from passing the globular stage; an embryo-lethal phenotype with seed arrestment has been observed⁶. Reduced expression of *MTA* in *A. thaliana* leads to decreased m⁶A level in mRNA and abnormal growth with reduced apical dominance, abnormal organ definition and increased trichome branching²¹. These data demonstrate that m⁶A in mRNA plays a functional role in plant development.

To further investigate the functions of m⁶A and to facilitate future studies of m⁶A in plants, we report here transcriptome-wide m⁶A profiling in two accessions of *A. thaliana*, Can-0 and Hen-16. These accessions are wild-collected natural lines from the two extremes of the natural range of photosynthetically active radiation (PAR) in the spring²². We show that m⁶A is a highly conserved RNA modification in mRNA across these two accessions. Intriguingly, m⁶A in *A. thaliana* is enriched not only around the stop codon and within 3' UTRs, as in yeast and mammalian systems, but also around the start codon, a property distinct from other known m⁶A methylomes^{17,18}. A positive correlation between m⁶A deposition and mRNA levels indicates a regulatory role of m⁶A in plant gene expression.

Results

m⁶A is abundant and conserved in *A. thaliana* mRNA. m⁶A is known to be a relatively abundant internal modification in

A. thaliana mRNA⁶. We selected ten geographically diverse accessions of *A. thaliana* to grow in a common laboratory environment to measure the m⁶A/A ratio of purified mRNA (Supplementary Table 1). These wild-collected natural lines were collected from sites that vary widely in PAR values²². We observed that the ratio of m⁶A/A in total mRNA from these ten accessions varied within the range of 0.45–0.65% (Fig. 1a), although not in direct relation to PAR, suggesting that the m⁶A methylation level in mRNA is relatively stable but potentially affected by complex environmental factors.

To obtain the transcriptome-wide m⁶A map of whole *A. thaliana* plants, we interrogated two accessions (Can-0 and Hen-16) using the m⁶A-targeted antibody coupled with high-throughput sequencing^{17,18}. Can-0 was originally collected from the Canary Islands where PAR in spring is 123.74, the highest seen for 1,191 accessions of *A. thaliana*²². Hen-16 was obtained from northern Sweden where spring PAR is 55.29 (ref. 22), the lowest end of the range. The m⁶A level in mRNA isolated from Can-0 is higher than that from Hen-16 as measured by LC-MS/MS (Fig. 1a).

More than 70% of the m⁶A peaks of Can-0 and Hen-16 were consistently detected in two biological replicates for each accession. We used these recurrent peaks as high-confidence m⁶A sites for further analysis. In total, we identified 7,489 m⁶A peaks representing the transcripts of 6,289 genes in Can-0, and 6,094 m⁶A peaks representing transcripts of 5,416 genes in Hen-16 (Supplementary Data 1). Among them, 4,317 m⁶A peaks were detected within both Can-0 and Hen-16 ($P < 1e-5$, Chi-squared test), indicating that m⁶A is highly conserved across *A. thaliana* accessions (Fig. 1b,c, Supplementary Data 1). We validated 11 m⁶A peak-containing genes by PCR with quantitative reverse transcription (RT-qPCR) and all of them showed significant enrichment in immunoprecipitation (IP)-pull-down samples (Supplementary Fig. 1). On the basis of these results, we estimated that the *A. thaliana* transcriptome contains 0.5–0.7 m⁶A peaks per 1,000 nucleotides or 0.7–1.0 m⁶A peaks per actively expressed transcript (Supplementary Table 2, Supplementary Fig. 2). These levels are comparable with those obtained in mammals¹⁷. The relative abundance of m⁶A peaks in mRNAs from Can-0 and Hen-16 is consistent with total m⁶A levels measured in mRNAs isolated from these two accessions (Fig. 1a,b).

To determine if the m⁶A peaks that we identified contained the m⁶A consensus sequence of RRACH (where R represents purine, A is m⁶A and H is a non-guanine base)^{23,24}, we analyzed the top 1,000 most significant peaks (Supplementary Fig. 3). We found at least one such motif in 934 peaks (Fig. 1d). The same sequence motif appears to be necessary for m⁶A methylation in plant mRNA as it has been observed in mammals and yeast mRNA (Supplementary Fig. 4)^{17–19}.

m⁶A distribution exhibits a distinct topology in *A. thaliana*.

We next analyzed the distribution of m⁶A in the whole transcriptome for both strains of *A. thaliana*. We determined the distribution of m⁶A reads along transcripts in the m⁶A-IP and non-IP (input) samples, respectively. Intriguingly, we found that the reads from m⁶A-IP are highly enriched around the start codon, stop codon and within 3' UTRs in both strains (Fig. 2a and Supplementary Fig. 5). The prevalence of m⁶A-IP reads around the start codon has not been observed in mammals or yeast.

To further confirm the preferential locations of m⁶A on transcripts, we investigated the metagene profiles of m⁶A peaks. Consistent with the distribution of reads, m⁶A peaks are abundant near the stop codon (61%) and start codon (16%),

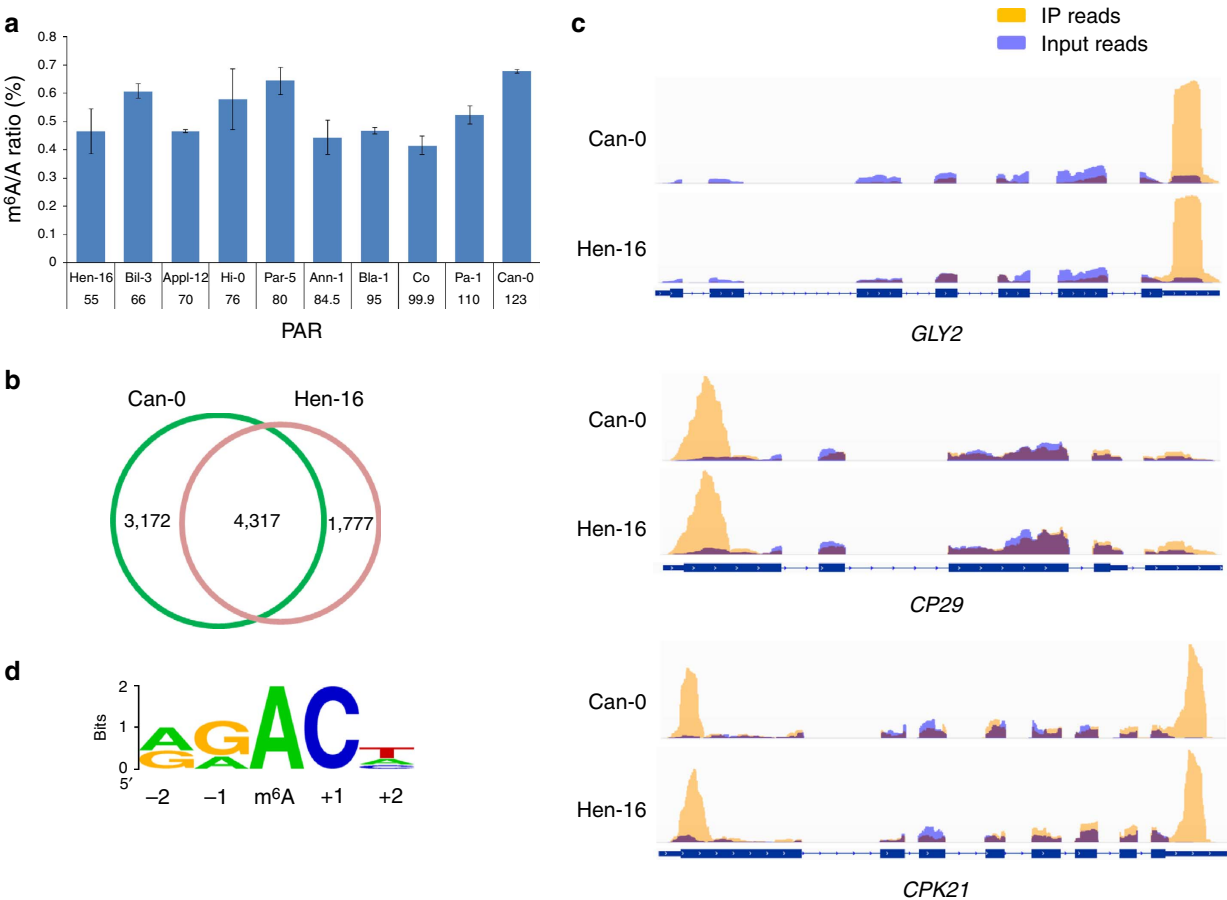


Figure 1 | Overview of m⁶A methylome in *A. thaliana*. (a) The m⁶A/A ratio of mRNA isolated from each *A. thaliana* strain. Error bars are calculated as the s.d. from three replicates. PAR values are displayed below the strain names. (b) Numbers of strain-specific and common m⁶A peaks. (c) Examples of m⁶A peaks conserved between Can-0 and Hen-16. Orange colour represents IP reads, while blue colour represents input reads. The purple colour comes from mixing orange with blue. (d) The RRACH conserved sequence motif for m⁶A-containing peak regions.

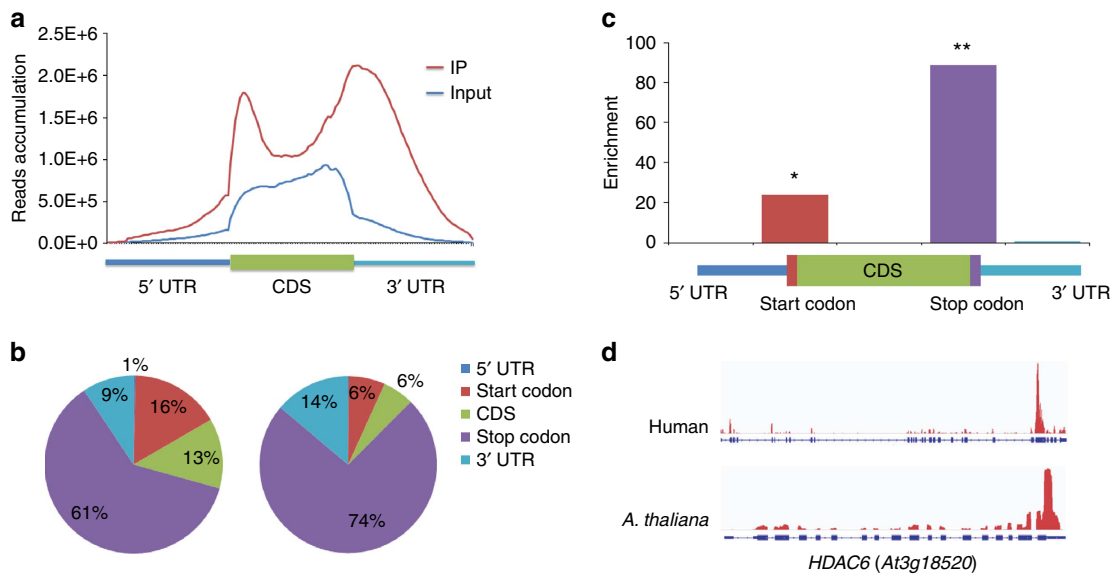


Figure 2 | Distribution pattern of m⁶A peaks along transcripts. (a) Accumulation of m⁶A-IP reads along transcripts. Each transcript is divided into three parts: 5' UTRs, CDs and 3' UTRs. (b) The m⁶A peak distribution within different gene contexts. Left panel: total genes with m⁶A peaks; right panel: genes conserved in human and *Arabidopsis*. (c) The m⁶A peak distribution along a metagene. Enrichment scores are calculated as $\frac{n}{N}/p$; n , number of peaks belonging to each category; N , number of total peaks; p , proportion of each category within the genome by length. $P < 2.2e - 16$, $**P < 1e - 30$. P values are determined by Chi-squared test. (d) An example of homologous genes with m⁶A peaks conserved in human and *A. thaliana*. CDs, coding regions.

followed by the coding regions (13%) and then 3' UTRs (9%) (Fig. 2b). After segment normalization by the total length of each gene portion, we observed that m⁶A is exclusively enriched around the start codon and stop codon (Fig. 2c). We mapped the number of m⁶A peaks around the start codon, the stop codon and upstream of transcription termination site (Supplementary Fig. 6a–c). The m⁶A peaks are enriched at three locations: the region 60 bp downstream and 50 bp upstream of the start codon, the region 80 bp downstream and 100 bp upstream of the stop codon and the region 80–220 bp before the poly(A) tail; the last location of enrichment is consistent with the previous finding that m⁶A preferentially locates at the 3' end of transcripts in a region 100–150 bp before the poly(A) tail in *Arabidopsis*²¹. We focused on the m⁶A peaks near the start codon and identified several new sequence motifs by comparing peak regions with scrambled background sequences, suggesting the possibility that distinct sequence motifs may exist for m⁶A methylation in plant mRNA (Supplementary Fig. 7).

Using strict criteria of peptide similarity, we identified 1,684 m⁶A-containing transcripts/genes in *A. thaliana* that are conserved in humans. Through comparison with the published data¹⁷, we found that 813 of these transcripts (48%) are also methylated in humans (Supplementary Data 2). Interestingly, almost all of the conserved methylated sites are located at the stop codon (74%) and 3' UTRs (14%) of transcripts (Fig. 2b,d), thus highlighting that m⁶A peaks around the start codon are specific to *A. thaliana*. We depicted the m⁶A peak distribution along transcripts in available data sets of human and mouse, confirming the observation that m⁶A is exclusively enriched at the stop codon and 3' UTRs in these systems (Supplementary Fig. 8). Clearly, the enrichment of m⁶A near the start codon in *A. thaliana* is distinct. This feature of the m⁶A distribution may play a unique role in plant-specific pathways.

m⁶A-containing mRNAs in important biological pathways. The presence of m⁶A is critical for normal plant development^{6,21}. To uncover further functional insights about m⁶A in *A. thaliana*, we selected genes containing m⁶A in both Can-0 and Hen-16 and identified the enriched gene ontology (GO) terms using the DAVID tool. We found that these genes are highly enriched in chloroplast/plastid and protein transport/localization categories (Fig. 3a).

We next sought to determine if the unique m⁶A position patterns are related to plant-specific GO categories. We classified genes into four subgroups according to the distribution of m⁶A peaks: PeakStart (m⁶A peaks around start codon), PeakStop (m⁶A peaks around stop codon), PeakBoth (m⁶A peaks around both start and stop codons) and others (Fig. 3b and Supplementary Data 1). Then we performed GO-enrichment analysis for each subgroup. All subgroups of m⁶A-containing genes exhibit high enrichment of chloroplast-related cellular components, indicating that a large proportion of these genes produce proteins localized in chloroplast though encoded by nuclear genome (Supplementary Fig. 9). Strikingly, >60% of genes belonging to the PeakBoth subgroup could be attributed to chloroplast components (Fig. 3c). Similarly, about 40% of the genes belonging to the PeakStart subgroup are associated with chloroplast. Photosynthesis is one of the most important functions in plants; 10–20% of nuclear genes encode proteins that are imported to chloroplast²⁵. Apparently, genes with m⁶A enrichment around the start codon are highly enriched in chloroplast components.

The significant enrichment of chloroplast-related GO categories among transcripts with m⁶A peaks around the start codon prompted us to examine photosynthesis-related genes in

PeakStart and PeakBoth subgroups. Indeed, we identified dozens of well-studied photosynthesis-related genes that carry m⁶A peaks (Supplementary Data 3). For instance, *At5g01920* (or STN8) is an important chloroplast thylakoid protein kinase that is specific to the phosphorylation of N-terminal threonine residues in D1, D2 and CP43 proteins and Thr-4 in PsbH of the photosystem II²⁶. In our m⁶A-IP data, the transcript of STN8 contains two clear m⁶A peaks around the start and stop codons (Fig. 3d). The large fraction of m⁶A-containing genes associated with chloroplast suggests a relationship between m⁶A mRNA methylation and photosynthesis, one of the defining processes of plants.

Strain-specific m⁶A marking of mRNAs. Although most m⁶A peaks are shared between the two *A. thaliana* strains, we could detect a proportion of strain-specific peaks, even using strict criteria (Methods). In total, we identified 1,319 Can-0-specific peaks and 546 Hen-16-specific peaks (Supplementary Data 4). Furthermore, some of the common m⁶A peaks in these two strains showed altered intensity (Fig. 4). GO analysis indicated that the genes with dynamic m⁶A peaks are enriched in several categories of fundamental biological functions including mRNA metabolic process, response to stimulus and regulation of translational elongation (Supplementary Data 5). For instance, *At5g06290* (or 2-Cys Prx B) has been shown to be sensitive to light intensities and oxidative stress²⁷. In our m⁶A-IP data, we observed significant m⁶A peaks around the start codon of *At5g06290* in Can-0 but not in Hen-16 (Fig. 4).

As an initial exploration into the functional implications of m⁶A methylation differences across genomes, we asked whether m⁶A methylation could underlie expression differences. Using the RNA-Seq data, we calculated gene expression to assign differentially expressed genes (DE genes) of the two strains. Indeed, we found 801 more highly expressed genes in Can-0 (Can-high) and 1,011 more highly expressed genes in Hen-16 (Hen-high) (Fig. 5a and Supplementary Data 6), perhaps reflecting, at least in part, the substantial differences in PAR in the native habitat of these accessions. Within the Can-high list, we detected many more genes that contained m⁶A peaks in Can-0 than in Hen-16 (195/81, *P* < 0.01, Fisher's exact test). Correspondingly, in the list of Hen-high genes, we detected more genes containing m⁶A peaks in Hen-16 than in Can-0 (221/140, *P* < 0.01, Fisher's exact test) (Fig. 5a). This observation suggests that each strain possesses its own characteristic m⁶A methylation sites that appear to be associated with gene activation. This hypothesis seems to contradict the recent discovery that a main function of m⁶A is to mediate mRNA degradation in mammalian cells^{11–13,20}. However, when we checked positions of the m⁶A peaks involved in upregulated genes, we found that a large portion of these peaks are located at the 5' end of the corresponding DE genes (Supplementary Data 6). To confirm this observation, we divided strain-specific m⁶A-containing genes into two groups and examined how their expression levels correlate with the locations of m⁶A peaks. Our analysis showed that m⁶A peaks at the 5' end of transcripts correlate with higher expression levels of each strain. Genes in the PeakStart category possesses higher overall expression levels and correlate well with strain-specific m⁶A peaks (Fig. 5b, note that the gene expression ratios of Can-0/Hen-16 are shown). We further examined the fraction of each subgroup of genes based on their expression levels. Genes with both 5'- and 3'-m⁶A peaks (PeakBoth) are enriched in the high-expression fraction, while genes with m⁶A peaks at other locations (PeakOther) tend to be lower expressed (Fig. 5c). Thus, m⁶A enrichment at the 5' end of the plant transcripts correlates with higher expression level in *A. thaliana* in general,

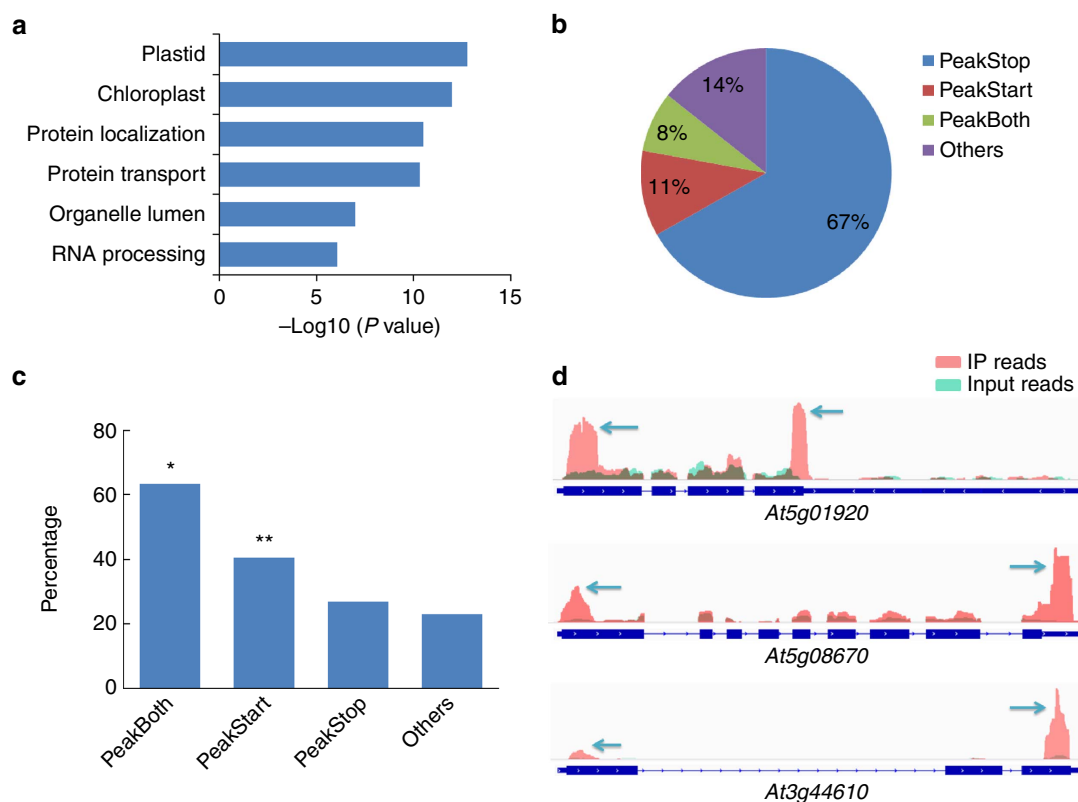


Figure 3 | Functional annotation of genes with m⁶A. (a) GO-enrichment analysis of all the genes with m⁶A peaks. GO categories are maintained by Gene Ontology Consortium. *P* values are calculated using the DAVID tool. (b) Percentages of subgroups of genes divided by the position pattern of m⁶A peaks. (c) Percentages of genes characterized as chloroplast related for each subgroup. * $P < 6.0 \times 10^{-25}$ (PeakBoth), ** $P < 5.2 \times 10^{-18}$ (PeakStart). *P* values are calculated using the DAVID tool. (d) Examples of chloroplast genes with m⁶A peaks at both the start and stop codon. The m⁶A-IP peaks are indicated by arrows.

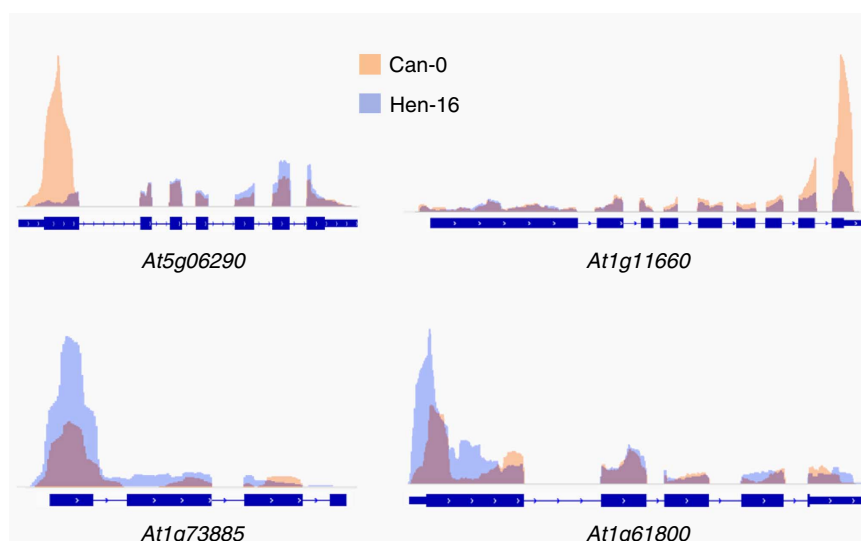


Figure 4 | Dynamic m⁶A peaks in two *Arabidopsis* strains. Different colours illustrate the accumulation of m⁶A-IP reads from two accessions.

perhaps by stabilizing the transcripts via reader proteins or interaction with translation machineries.

In a recent study, Bodi *et al.*²¹ generated an m⁶A reduction mutant of *A. thaliana* and profiled gene expression. They identified 883 upregulated and 654 downregulated genes in the mutant plant²¹. By comparing the DE genes with our list of m⁶A peaks, we found that 116 among 883 upregulated transcripts are modified by m⁶A, whereas 142 among 654 downregulated

transcripts contain m⁶A (Supplementary Data 7). These data suggest that transcripts carrying m⁶A tend to be downregulated in the m⁶A reduction mutant ($P < 0.01$, Chi-squared test). We extended this analysis to the whole transcriptome. Indeed, among genes with m⁶A modification, more are downregulated than upregulated in the m⁶A reduction mutant plant. This trend did not exist for genes without m⁶A modification (Fig. 5d). Together, their data supported our hypothesis that m⁶A tends to positively

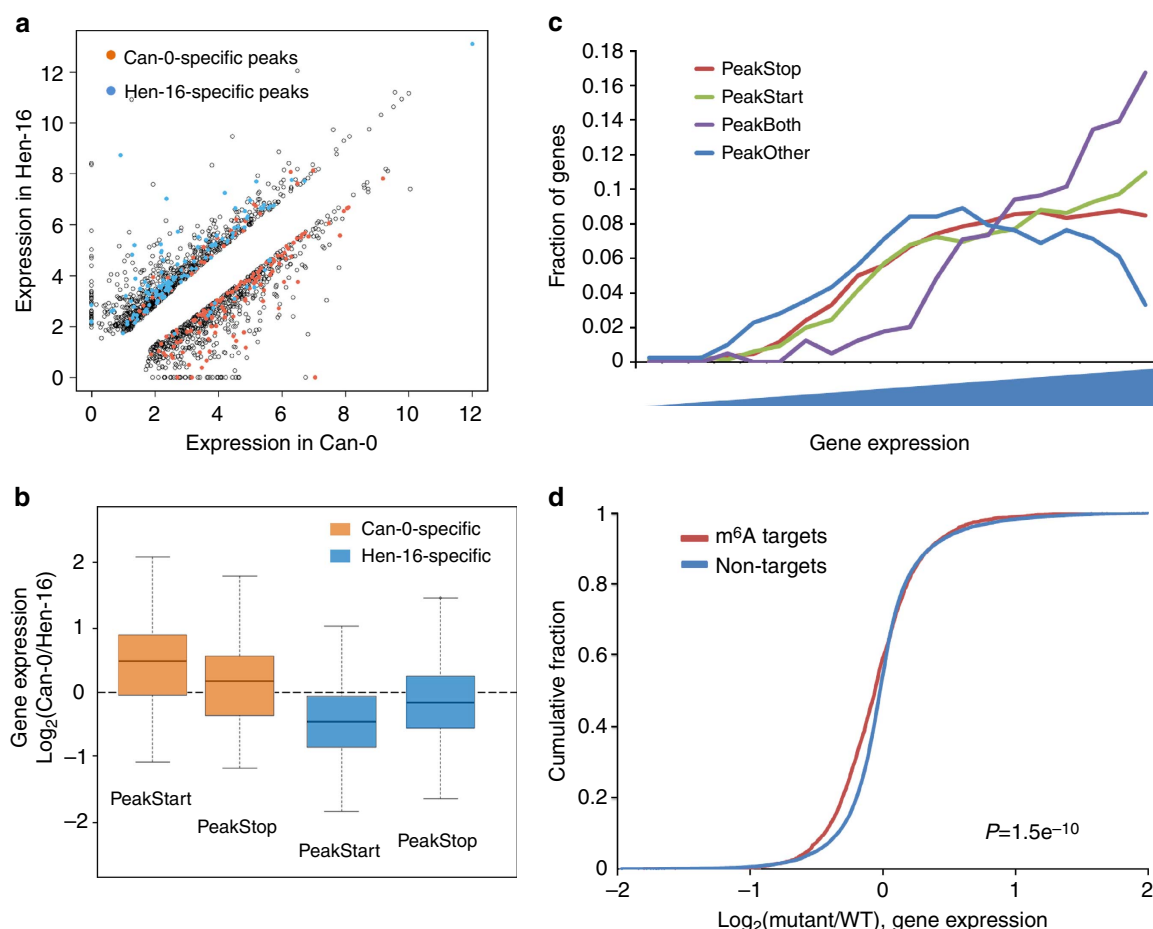


Figure 5 | Relationship between m⁶A peaks and mRNA level. (a) Differentially expressed mRNAs in Can-0 and Hen-16. Genes with Can-0-specific m⁶A peaks are highlighted in orange and genes with Hen-16-specific m⁶A peaks are highlighted in blue. (b) The ratio of mRNA expression levels in two samples containing strain-specific m⁶A peaks. Genes are divided into two categories (PeakStart and PeakStop) according to the peak positions. (c) Fraction of genes belonging to each subgroup defined by the m⁶A distribution pattern. Genes are sorted by expression levels. (d) Cumulative distribution of mRNA expression changes between the *mta* mutant and WT for m⁶A-modified genes (red) and non-target genes (blue). *P* values are calculated by two-sided Mann-Whitney test. WT, wild type.

correlate with gene expression in a large fraction of transcripts in *A. thaliana*.

Mammalian microRNA (miRNA)-binding sites are mostly found within 3' UTRs²⁸; however, in plants they occur typically in the coding regions of target transcripts²⁹. Unlike mammals, miRNAs in plants recognize the target sites by near-perfect sequence complementarity. By comparing the transcripts containing m⁶A with the public miRNA targets database (TAIR)³⁰, we found that only 5% of known miRNA-targeted transcripts contain m⁶A. Furthermore, we employed a *de novo* miRNA target prediction method³¹ to inspect m⁶A peak regions. Among the top 1,000 most significant m⁶A peak regions, only 11 regions could be potentially targeted by miRNA (Supplementary Data 8). Taken together, our results indicate that m⁶A is unlikely to directly impact miRNA binding sites in *A. thaliana*, although such an association has been proposed in animals¹⁸. However, we could not exclude the possibilities that m⁶A may affect miRNA maturation, or impact miRNA targeting sites through reader proteins of m⁶A or structural changes induced by methylation.

Discussion

The discovery of m⁶A demethylases and the mapping of the m⁶A methylomes in mammalian systems indicate that m⁶A

methylation of mRNA is a reversible and dynamic process with regulatory functions^{14–18,32,33}. The importance of m⁶A in post-transcriptional regulation of gene expression is further reinforced by the discovery and characterization of mammalian reader proteins that recognize m⁶A modifications of mRNA and subsequently affect the stability of the target transcripts²⁰. Previous studies have shown that m⁶A plays a critical role in plant development^{6,21}. Here, we report the transcriptome-wide m⁶A distributions in two accessions of *A. thaliana*, Can-0 and Hen-16. We found that m⁶A is highly conserved across *A. thaliana* accessions. The methylation sites in a portion of transcripts are also conserved in corresponding transcripts of humans, indicating a fundamental functional role of m⁶A in eukaryotes. Nevertheless, there are differences between the two *A. thaliana* accessions with a higher total m⁶A level in Can-0 than Hen-16, and with ~1,400 more m⁶A peaks identified in Can-0. The m⁶A distribution could be influenced by differences in the accession's climates of origin and genetic backgrounds. The modification sites could be conserved but the modification fraction at each site could vary depending on environmental factors.

Importantly, we discovered features of the m⁶A distribution in *A. thaliana* mRNA that are distinct from those of mammals: (i) m⁶A in both accessions is enriched around the stop codon and

at 3' UTRs, as it has been found in mammals, but also around the start codon; (ii) the m⁶A methylation around the start codon is heavily associated with the chloroplast, a photosynthesis organelle in plants. In addition, m⁶A is less likely to be directly associated with miRNA recognition sites in *A. thaliana*. These distinct differences, namely the start codon enrichment of m⁶A and its association with chloroplast, strongly suggest additional, plant-specific functions of this mRNA methylation. Previous studies indicated that the currently available m⁶A antibody could also recognize N⁶,2'-O-dimethyladenosine (m⁶Am)^{17,19}, which might lead to enrichment peaks at transcription start site. However, in our results, the start codon enrichment is clearly distinct from the m⁶Am peak observed previously¹⁷ (Fig. 1). More accurate, base-resolution methods are highly desirable to determine the exact sites and modification fractions in the future.

Noticeably, the distinct enrichment of m⁶A around the start codon correlates with the overall upregulation of mRNA expression level. This relationship contradicts observations in mammalian systems, in which m⁶A methylation around the stop codon and at 3' UTRs is negatively correlated with gene expression^{11,12,20}. Published microarray data using a different accession of *Arabidopsis* (Col-0) also supports our findings with high correlations with our RNA-seq data (Supplementary Fig. 10)²¹. Although our analysis demonstrates significant overlap of m⁶A sites between the two ecotypes (Can-0 and Hen-16), more precise analysis would benefit from future studies on coincident accessions. Our results suggest that m⁶A reader proteins may exist in *A. thaliana* to recognize m⁶A at the 5' end and subsequently affect the stability of the target mRNA. This function could directly impact translation through the methylation itself or through the reader protein(s). It should be noted that several RNA-binding proteins have been pulled down as potential 'm⁶A readers' with a few biochemically confirmed to specifically recognize methylated mRNAs^{17,20}. In particular, YTHDF2 has been shown to bind and accelerate the decay of m⁶A-modified mRNA²⁰. However, the functions of other m⁶A readers are still unknown; some of them could promote translation of a specific set of transcripts. Our discovery suggests the versatile roles of m⁶A in plants beyond mediating mRNA decay.

It has been demonstrated that m⁶A methyltransferase in *A. thaliana* is critical for normal plant development^{6,21}. We found that the transcripts with m⁶A are highly enriched in chloroplast/plastid and protein transport/localization categories, indicating a mechanism by which m⁶A affects plant-specific metabolism. Past studies have demonstrated that light and circadian cycles impact the stability and translation of specific plant transcripts^{34–37}. However, the mechanisms of post-transcriptional gene regulation in response to light availability have not been clearly understood. The stability and translation of chloroplast mRNAs are known to be regulated by RNA-binding proteins that reside at 5' and 3' UTRs³⁸. Intriguingly, our data show that >60% of mRNAs containing m⁶A at both the start and stop codons encode proteins that could be components of the chloroplast (Fig. 3c). Given that 10–20% of nuclear-encoded genes are associated with the chloroplast and photosynthesis in plant²⁵, this percentage represents a significant enrichment. It is possible that the dynamic m⁶A methylation at 5' and 3' ends modulate the RNA affinities of RNA-binding proteins, thereby controlling mRNA transport and localized expression. Though technologies that can provide more accurate measurements of the m⁶A sites are required in the future to gain deeper insights (for example, splicing), the first m⁶A transcriptome-wide map of a plant species *A. thaliana* presented here provides a starting roadmap for uncovering m⁶A functions that may affect/control plant metabolism in the future.

Methods

Plant material. Seeds from the Can-0 and Hen-16 accessions of *A. thaliana* were sown in 50:50 Metromix 200:Farfad C2 soil in 48-cell flats and stratified for 5 days at 4 °C to synchronize germination. Seedlings were germinated in controlled-environment growth chambers at the University of Chicago greenhouses on a 16-hour light and 8-hour dark cycle. Plants were thinned between days 5 and 7 of growth. Above-ground tissue was harvested between the fifth and seventh hour of the light cycle on day 21. The tissue was flash frozen in liquid nitrogen, ground using a mortar and pestle and stored at –80 °C.

High-throughput m⁶A sequencing. To obtain sufficient (10 mg) total RNA for IP of m⁶A-containing mRNA, ~200 plants from each accession were harvested and pooled in 0.6 and 2.1 g quantities. RNA was extracted using a protocol modified from a published procedure³⁹; reactions took place in 15 or 50 ml conicals, and reagents were scaled up linearly with respect to the increased tissue mass, with 20 or 70 times the amount of each reagent, respectively. RNA was tested for quality via Nanodrop and gel electrophoresis. Polyadenylated RNA was extracted using FastTrack MAG Maxi mRNA isolation kit (Invitrogen). RNA was randomly fragmented to ~200 nt by RNA Fragmentation Reagents (Ambion). Fragmented RNA was incubated for 2 h at 4 °C with m⁶A antibody (Synaptic Systems Cat. No. 202003, diluted to 0.5 µg µl^{–1}) in IP buffer (50 mM Tris-HCl, 750 mM NaCl and 0.5% Igepal CA-630) supplemented with BSA (0.5 µg µl^{–1}). The mixture was then incubated with protein-A beads and eluted with elution buffer (1 × IP buffer and 6.7 mM m⁶A). Eluted RNA was precipitated by 75% ethanol. The eluted RNA was treated with RNasin (Ambion Cat No. AM2694) according to the manufacturer's instructions. TruSeq Stranded mRNA Sample Prep Kit (Illumina) was used to construct the library from immunoprecipitated RNA and input RNA according to a published protocol⁴⁰. Sequencing was done on an Illumina HiSeq machine with 2 × 100 cycles Solexa paired-end sequencing.

RT-qPCR validation for m⁶A-enriched genes. Eleven genes enriched in the m⁶A-IP and six genes not differentially expressed between the IP and non-IP samples were tested by RT-qPCR. Data cleanup and analysis proceeded as described by previous protocol⁴¹. The dissociation curves for each reaction were plotted and those with irregular features were removed. RNA passed through a beads only column, which should not bind any RNA, was treated as the input control for the IP step. Ct values from qPCR on the flow-through from the m⁶A-IP and the m⁶A-IP were expressed as the percent input of the beads only sample. Primer sequences are listed in Supplementary Data 9. Detailed information for plotting the qPCR figure can be found in an online manual at: <http://www.lifetechnologies.com/us/en/home/life-science/epigenetics-noncoding-rna-research/chromatin-remodeling/chromatin-immunoprecipitation-chip/chip-analysis.html>.

Data analysis. Sequence data were analyzed according to the procedure described by Meyer *et al.*¹⁸ Briefly, Tophat⁴² with Bowtie⁴³ was run to align the input and IP-sequenced samples to the Columbia reference genome and annotation file (Tair10)³⁰. The BEDTools tool⁴⁴ was used to divide the aligned accepted hits into 1 bp intervals. The read depth was then averaged for each 25 nt discrete, non-overlapping genomic window using an *ad hoc* R program (Supplementary Data 10). To identify 25 nt windows enriched for m⁶A, the number of reads that mapped to each window for the IP and input sample, and the total reads for each, were compared using Fisher's exact tests and corrected for multiple testing using Benjamini–Hochberg to reduce false discovery rate to 0.05. To determine which of these windows cluster to form distinct peaks, we concatenated adjacent significant windows together and filtered out peaks <100 nt in length. Significant peaks with false discovery rate <0.05 in Can-0, Hen-16 or both were annotated using an *ad hoc* R script (Supplementary Data 10). IntersectBED with the Columbia reference genome and annotation file was used to further annotate this set of significant peaks⁴⁴. Peaks that shared >50% overlapping length were defined as recurrent peaks. For a peak to be classified as strain specific, it should not overlap (one nucleotide) any peak in any two replicates of the other strain. Sequence motifs were identified by using Homer⁴⁵. Gene expression was calculated by Cufflinks⁴² using the input-sequencing reads. Cuffdiff⁴² was used to find the DE genes between Can-0 and Hen-16. Gene function analysis (GO enrichment) was performed with the DAVID tool⁴⁶. Plant miRNA targets were predicted by psRobot³¹. Microarray data were downloaded from GEO (accession ID: GSE349243) and RMA method⁴⁷ was introduced to calculate gene expression and DE genes between *mta* mutant and wide type.

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Author contributions

C.H., J.B. and G.J. conceived the project; C.H., J.B. and G.J. designed most experiments; G.Z.L., A.M. and Z.L. performed data analyses; G.J., A.M., G.Z. and H.D. performed the experiments; and G.Z.L., G.J. and C.H. wrote the paper with suggestions from J.B.

Additional information

Accession codes: The high-throughput data used in this study are deposited in the NCBI GEO database with accession number GSE59154.

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