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Chapter 11

Chemical RNA Modifications: The Plant Epitranscriptome

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Celso Gaspar Litholdo Jr and Cécile Bousquet-Antonelli

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Abstract RNA post-transcriptional modifications create an additional layer to control mRNA transcription, fate, and expression. Considering that they are non-genetically encoded, can be of reversible nature, and involved in fine-tuning gene expression, the landscape of RNA modifications has been coined the “RNA epigenome” or “epitranscriptome.” Our knowledge of the plant epitranscriptome is so far limited to 3′-uridylation and internal m⁶A and m⁵C modifications in Arabidopsis. m⁶A is the most abundant and well-studied modification on mRNAs, and involves the activities of evolutionarily conserved “writer” (methyltransferase), “reader” (RNA binding proteins), and “eraser” (demethylases) proteins. In Arabidopsis, m⁶A is crucial for embryogenesis, post-embryonic growth, development, phase transition, and defense responses. Conversely to animals, our understanding of the roles of m⁶A is limited to the finding that it is an mRNA stabilizing mark. Yet likely to exist, its roles in controlling plant mRNA maturation, trafficking, storage, and translation remain unexplored. The m⁵C mark is much less abundant on the transcriptome and our knowledge in plants is more limited. Nonetheless, it is also an important epitranscriptomic mark involved in plant development and adaptive response. Here, we explore the current information on m⁶A and m⁵C marks and report knowledge on their distribution, features, and molecular, cellular, and physiological roles, therefore, uncovering the fundamental importance in plant development and acclimation of RNA epigenetics. Likely to be widespread in the green lineage and given their crucial roles in eukaryotes, the fostering of data and knowledge of epitranscriptome from cultivated plant species is of the utmost importance.

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[AU1]

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[AU2]

28 11.1 Chemical RNA Modifications: A New Layer of Post- 29 transcriptional Regulation

30 The pattern of gene expression of a cell is what determines its identity and activity.
31 Maintaining its homeostasis is hence crucial for any organism. However, cells must
32 also respond to developmental and environmental stimuli for organisms to develop
33 and grow, or to acclimate to external conditions. In such cases, their pattern of gene
34 expression needs to be adjusted, occasionally very fast. This reprogramming takes
35 place simultaneously at the transcriptional (Kaufmann et al. 2010; de Nadal et al.
36 2011; Lelli et al. 2012) and post-transcriptional levels (Mata et al. 2005; Zhao et al.
37 2017; Schaefer et al. 2018). Post-transcriptional regulation is exerted at pre-
38 messenger RNA (pre-mRNA) maturation (including transcription termination/
39 polyadenylation and splicing), mRNA intracellular trafficking (including nucleocy-
40 toplasmic and sub-compartment localization), storage, stability, and translation.
41 Regulation of the transcriptome is dependent on the primary genetic code, which
42 provides local structures and short sequences, either for binding of proteins that
43 form with the messenger RNA RiboNucleoProtein (mRNP) complexes or for comple-
44 mentary recognition by microRNAs (miRNAs).

45 In the last couple of years, the scientific community regained interest in RNA (in
46 particular mRNA) chemical modifications, and recognized that they create an addi-
47 tional layer to the control of mRNA transcription and fate. Considering that RNA
48 modifications are non-genetically encoded, they can display a reversible nature, and
49 fine-tune the fate and expression of transcripts harboring them. The landscape of
50 modifications deposited on the transcriptome (in particular on mRNAs) of a cell has
51 been coined the “RNA epigenome” (He 2010) or “epitranscriptome” (Meyer et al.
52 2012; Saletore et al. 2012).

53 In all three domains of life (Archaea, Bacteria, and Eukarya) as well as in viruses,
54 RNAs carry chemical modifications. More than 110 distinct modifications ([http://
55 mods.rna.albany.edu/mods/](http://mods.rna.albany.edu/mods/)) have been recognized across all domains of life and
56 across all types of RNAs [mRNAs, ribosomal RNAs (rRNAs), transfer RNAs
57 (tRNAs), long noncoding RNAs (lncRNAs), circular RNAs (circRNAs), and small
58 noncoding RNAs (sRNAs)] but the roles of the vast majority of them remain
59 unknown (Li and Mason 2014). Although highly debated until 2012, the existence
60 of chemical modifications deposited on mRNAs is now well recognized and docu-
61 mented in several eukaryotes, such as yeast, mammals, and plants, as well as
62 recently in bacteria (Deng et al. 2015; Hoernes et al. 2015). In addition to the 5' cap
63 and 3'-poly(A) tail, eukaryotic mRNA 3'-extremities can be modified by the non-
64 templated addition of uridines (uridylation; de Almeida et al. 2018a) and/or carry
65 internal modifications, which can be of over 15 different types ([http://mods.rna.
66 albany.edu/mods/](http://mods.rna.albany.edu/mods/); Song and Yi 2017).

67 The most common of the internal nucleotide modifications consists in the addi-
68 tion of a methyl group to the 2'-O position of the ribose moiety. In addition, up-to-
69 date transcriptome-wide mapping on mRNAs and functional data are available on
70 transcripts that can be edited by deamination of adenosine to inosine (A-to-I editing;

Yablonovitch et al. 2017; Sinigaglia et al. 2018) or carry N¹-methyladenosine (m¹A; 71
 Dominissini et al. 2016), N⁶-methyladenosine (m⁶A; Dominissini et al. 2013), 72
 5-methylcytosine (m⁵C; Squires and Preiss 2010), N⁴-acetylcytidine (ac⁴C; Arango 73
 et al. 2018), pseudouridine (Ψ; Schwartz et al. 2014a; Carlile et al. 2014), or 74
 hydroxymethylcytosine (h⁵mC) (Fig. 11.1a, b). Additional modifications include 75
 the N⁶-2'-O-dimethyladenosine (m⁶Am) and 5-hydroxymethylcytosine (h⁵mC) 76

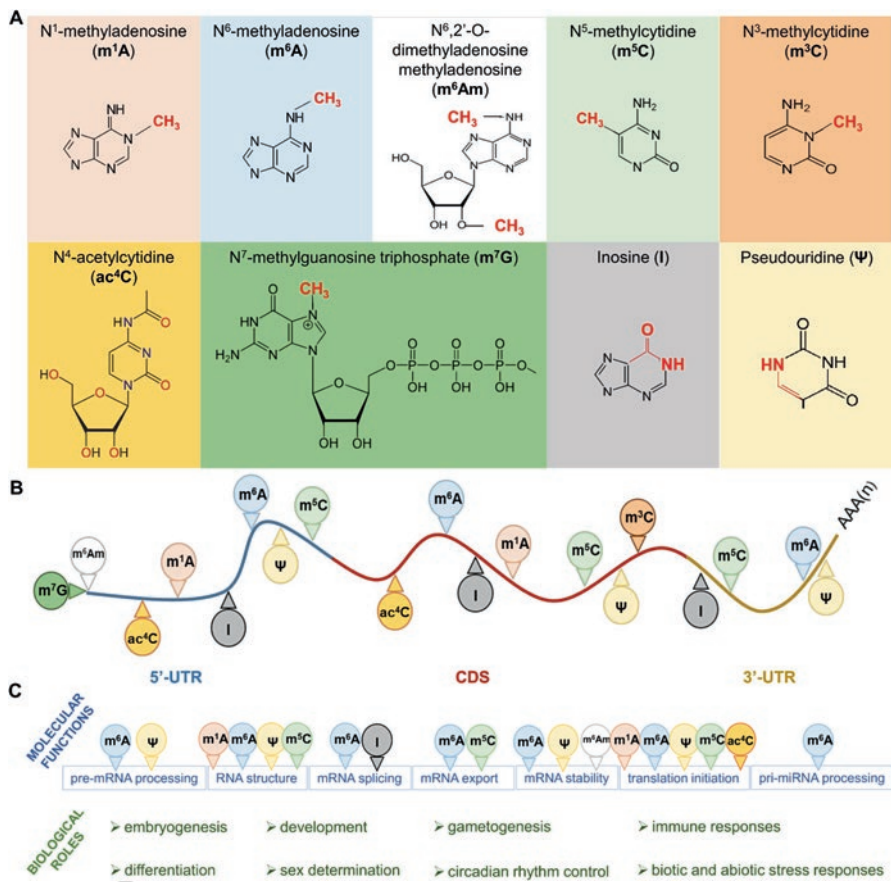


Fig. 11.1 The epitranscriptome landscape. (a) The major post-transcriptional modifications deposited on the transcriptome of mammalian cells are N¹-methyladenosine (m¹A), N⁶-methyladenosine (m⁶A), N⁶,2'-O-dimethyladenosine methyladenosine (m⁶Am), N⁵-methylcytosine (m⁵C), N³-methylcytosine (m³C), N⁴-acetylcytidine (ac⁴C), N⁷-methylguanosine triphosphate (m⁷G), inosine (I), and pseudouridine (Ψ). (b) An RNA polymerase II transcribed RNA is represented, including the 5'-cap structure, which is a modified 7-methylguanosine (m⁷G) linked via an unusual 5' to 5' triphosphate linkage to mRNA, and the 3'-end poly(A) tail (AAA(n)). For each particular RNA chemical modification, a representation is shown in relation to mRNA position (5' UTR, blue; CDS, red or 3' UTR, yellow). (c) The molecular consequences of each RNA marks and the biological roles of these modifications are also represented. It is important to mention that only m⁶A and m⁵C modifications have been identified so far in the plant epitranscriptome

77 (Song and Yi 2017; Frye et al. 2018). These modifications can regulate all steps of
78 an mRNA life (Fig. 11.1c) and can even recode open reading frames (Powers and
79 Brar 2018). Several were proposed to be of a dynamic nature (i.e., they can be
80 erased) and their profiles found to be distinct across development or in response to
81 stress exposure. At the organism level, RNA modifications are required for differentia-
82 tion, development, gametogenesis, sex determination, embryogenesis, circadian
83 rhythm control, immune response, biotic and abiotic stress responses (Fig. 11.1c,
84 Sinigaglia et al. 2018; Song et al. 2018).

85 Except for the 5'-cap and poly(A)-tail, our knowledge of the plant epitranscrip-
86 tome is so far limited to uridylation (de Almeida et al. 2018a, b), m⁶A (Luo et al.
87 2014; Li et al. 2014c, 2018), and m⁵C (Cui et al. 2017; David et al. 2017). Plant
88 mRNAs are likely to carry other types of modifications but their existence and roles
89 remain to be explored. A-to-I editing though is absent from the plant nuclear trans-
90 criptome but organelle transcripts (chloroplast and mitochondria) carry C to U
91 edited bases, and in ferns and mosses also U-to-C changes (Takenaka et al. 2013).
92 Excellent reviews have recently been published on the synthesis, molecular, cellu-
93 lar, and physiological roles of uridylation (de Almeida et al. 2018a, b), and organelle
94 editing (Takenaka et al. 2013). We will hence focus the present chapter on the fea-
95 tures and functions of the internal m⁶A and m⁵C modification of messenger RNAs
96 in plants.

97 11.2 Roles and Features of the m⁶A Mark in Plants

98 11.2.1 General Features of the m⁶A Mark

99 The m⁶A mark is the most abundant and widespread of mRNA modifications. It has
100 been profiled on the polyadenylated transcriptome of the yeast *Saccharomyces cere-*
101 *visiae* (Schwartz et al. 2013) and of various human and mouse cell lines and tissues
102 (Dominissini et al. 2012; Meyer et al. 2012; Fustin et al. 2013; Schwartz et al. 2014b;
103 Wang et al. 2014; Chen et al. 2015). In higher plants, it has been mapped on rice cal-
104 lusus and leaves (Li et al. 2014c), in two distinct ecotypes of *Arabidopsis thaliana* (Luo
105 et al. 2014), and in mature leaves (Anderson et al. 2018), 5- and 14-day old seedlings
106 (Shen et al. 2016; Duan et al. 2017) and across several organs (leaves, flowers, and
107 roots; Wan et al. 2015) of *Arabidopsis Columbia-0* ecotype. Consistent with the evo-
108 lutionarily conserved nature of the m⁶A mark, several of its features were found to
109 be conserved across organisms and tissues. Transcriptome-wide, m⁶A represents
110 1–1.5% of the total number of adenosines on polyadenylated transcripts. It mostly
111 localizes in the 3'-UTRs, following the stop codon and in the last exons of transcripts
112 (Ke et al. 2015). A nucleotide sequence context around m⁶A is shared across eukary-
113 otes. Indeed, m⁶A is mainly confined at the consensus RRACH (where R = A/G and
114 H = U > A > C) and found in 70% of the cases at GAC. In mammals at least, the m⁶A
115 mark was detected on most, if not all, polymerase II transcribed RNAs, including

primary transcripts of miRNAs (Alarcon et al. 2015), lncRNAs, circRNAs, and mRNAs (Meyer et al. 2012; Dominissini et al. 2013; Schwartz et al. 2013).

In plants, a thin layer chromatography analysis of the m⁶A/A ratio on the polyadenylated transcriptome of Arabidopsis shows that it ranges from 0.9% in roots and leaves to 1.4% in flowers (Zhong et al. 2008) and that it is not randomly distributed, but mostly enriched at the 3'-end of transcripts (Bodi et al. 2012). Subsequently, next generation sequencing (NGS) profiling of the polyadenylated transcriptome found, both in rice and Arabidopsis, that the vast majority of the m⁶As peaks occur in the 3'-UTRs or overlap the stop codon (Li et al. 2014c; Luo et al. 2014; Anderson et al. 2018; Shen et al. 2016; Wan et al. 2015). These studies in rice and Arabidopsis also found that 10–15% of the detected m⁶A peaks are located around the start codon (Li et al. 2014c; Luo et al. 2014; Shen et al. 2016). The presence of some m⁶A marks around the start codon and in 5'-UTR is not restricted to plants, for instance, this has been observed in certain mammalian cells types and growth conditions (Dommissini et al. 2012; Zhou et al. 2015). Most of the m⁶A peaks were found to carry the RRACH consensus suggesting that this sequence motif is necessary also in plants for the deposition of the mark. However, recent findings support the idea that m⁶A sites could occur in sequence contexts other than RRACH [such as “GGAU” or URUAY (R = G > A, Y = U > A)] in Arabidopsis (Luo et al. 2014; Anderson et al. 2018; Shen et al. 2016; Wei et al. 2018) and rice (Li et al. 2014c). Whether other types of plant RNA polymerase II transcripts (such as pre-miRNAs, lncRNAs, and sRNA) are modified with m⁶A remains to be explored.

In mammals and flies at least, the m⁶A mark is deposited co-transcriptionally by a conserved heteromultimeric complex called the “writer” complex and can be reverted to unmodified adenines by demethylases tagged as “erasers” (see Sect. 11.2.2; Fig. 11.2). At the molecular level, the most prevalent role of m⁶As is to influence the binding of proteins to their RNA targets. They can either act to repel or attract RNA binding proteins (RBPs), the latter of which are known as “m⁶A readers” (Arguello et al. 2017; Edupuganti et al. 2017). Readers convey the m⁶A signal by directly controlling the fate of their RNA target and/or by recruiting effector proteins. The m⁶A mark recruits readers by two main processes. First, the reader may carry a YTH domain, an evolutionarily conserved RNA binding motifs whose folding forms a pocket that tightly accommodates the m⁶A residue (see Sect. 11.2.4; Fig. 11.2). Alternatively, the presence of m⁶A may positively influence the recruitment of RBPs by: (1) increasing their affinity for their RNA binding region, or (2) acting through alteration of RNA structures in a mechanism called “m⁶A-switch” (Zhou et al. 2016; Roost et al. 2015; Liu et al. 2015).

11.2.2 The Plant Writer and Eraser Systems

In 1994, Bokar and colleagues characterized and partially purified an mRNA N⁶-methyltransferase from HeLa cell nuclei. They found that it comprises a multisubunit complex composed of two fractionable subcomplexes: MT-A (200 kDa) and

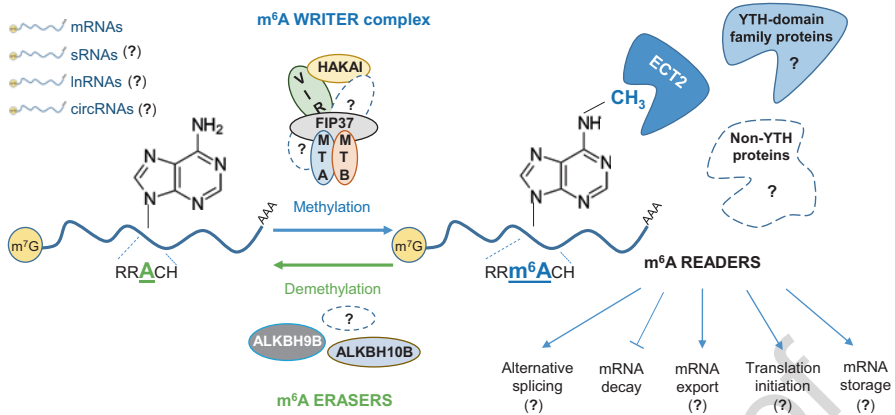


Fig. 11.2 The m⁶A modification regulatory system. The m⁶A mark is found in most, if not all, RNA polymerase II transcribed RNAs, including messenger RNAs (mRNAs), small RNAs (sRNAs), long noncoding RNAs (lncRNAs), and circular RNAs (circRNAs); except the latter, all contain the modified m⁷G nucleotide at the 5'-end and poly(A) tail at the 3'-end. A nucleotide consensus sequence RRACH (R = A/G, H = U > A > C) is mainly the site for the m⁶A writer complex, which includes the subunit methyltransferase proteins MTA, MTB, FIP37, VIR, and HAKAI. m⁶A-RNA pol II RNA demethylation is carried by two eraser enzymes, ALKBH9B and ALKBH10B. So far only m⁶A readers carrying a YTH-RNA binding domain have been identified in plants, which include the recently characterized ECT2 protein. The molecular role of m⁶A mark depends on the reader protein that binds to the modified nucleotide, generally in animals, directing the RNA to alternative splicing, mRNA decay, mRNA export, translation initiation, or mRNA storage. Question mark (?) indicates the unknown features of the plant m⁶A regulatory system

157 MT-B (875 kDa) containing the S-adenosyl-methionine-binding site and the RNA
 158 binding site, respectively (Bokar et al. 1994). The MT-A subcomplex carries on a
 159 70 kDa component, the methyltransferase player that was identified and named
 160 MT-A70 (Bokar et al. 1997). MT-A70 is conserved across eukaryotes and is known
 161 as METTL3 in mammals (Liu et al. 2014), IME-4 (Inducer of Meiosis-4) in *S. cere-*
 162 *visiae* (Yadav and Rajasekharan 2017) and *Drosophila melanogaster* (Lence et al.
 163 2016), and MTA70 in *A. thaliana* (Zhong et al. 2008).

164 Purification of the writer complex from animals (human and fly) confirmed that
 165 it is an heteromultimeric complex, whose catalytic core is composed of two RNA
 166 methyltransferases (METTL3 and METLL14) and the cofactor WTAP (fly Fl(2)d).
 167 METTL3 and 14 physically interact with each other and their association has a
 168 synergetic effect on the complex catalytic activity (Liu et al. 2014). METTL3 is the
 169 catalytically active component while METTL14, which has a degenerate methyl-
 170 transferase site, plays a scaffolding role that is critical for substrate recognition
 171 (Wang et al. 2016; Śledź and Jinek 2016). The animal writer complex contains other
 172 subunits: VIRMA (fly Virilizer), RBM15/RBM15B (fly spenito), Z3CeH13 (fly
 173 Xio/Flacc), and HAKAI (Ping et al. 2014; Yue et al. 2018; Haussmann et al. 2016;
 174 Lence et al. 2016; Guo et al. 2018; Knuckles et al. 2018; Patil et al. 2016). Zc3H13
 175 bridges the mRNA binding factor RBM15 to WTAP (Knuckles et al. 2018) and

VIRMA mediates preferential methylation by recruiting the METTL3/METTL4/ WTAP core complex to 3'-UTRs and near the stop codons (Yue et al. 2018).

Up to now, data on the plant writer complex comes from *A. thaliana* (Table 11.1; Zhong et al. 2008; Bodi et al. 2012; Ruzicka et al. 2017). Following the discovery by Bokar et al. (1997) that the methyltransferase activity of the writer complex was carried by METTL3, further characterization of the complex remained incomplete. It is in 2008 that the team of Rupert Fray ran the first functional study of an MTA70 protein and also identified FIP37 (the Arabidopsis homolog of WTAP) as a component of the writer complex (Zhong et al. 2008). Further biochemical characterization of the Arabidopsis writer complex showed that it also contains MTB (the plant homolog of METTL14), VIRILIZER, and HAKAI (Ruzicka et al. 2017). The Arabidopsis writer complex hence closely resembles the animal complex, but, whether it contains additional factors in particular homologs of RBM15 and Z3CeH13 remains to be explored. Every component of the Arabidopsis complex is found in the nucleoplasm. However, their nucleoplasmic distribution changes between root meristematic cells and cells in the root elongation zone. While showing a nucleoplasmic diffuse pattern in non-differentiated cells, they localize to nuclear speckles in dividing cells (Ruzicka et al. 2017). These observations support the idea that m⁶A deposition is likely co-transcriptional in plants, as in animals, and that the activity of the writer complex might be regulated. Total or partial loss of any of the five components, except for HAKAI, of the Arabidopsis writer complex drastically decreases the total levels of m⁶A in polyadenylated transcripts (Zhong et al. 2008; Ruzicka et al. 2017). HAKAI is not required for plant viability (see Sect. 11.2.3) and shows only a 35% reduction of m⁶A levels in loss-of-function mutants. Except for MTA70, which based on evolutionary analyses (Bujnicki et al. 2002) is a *bona fide* methyltransferase and homolog to METTL13, the molecular roles that other components carry out inside the writer complex remain to be uncovered in plants.

The m⁶A epitranscriptomic mark was proposed to be dynamic following two reports that identified mammalian FTO (fat mass and obesity) and ALKBH5 (the alkylation repair homolog protein) as specific RNA m⁶A demethylases, both *in vitro* and *in vivo* (Jia et al. 2011; Zheng et al. 2013). They both belong to the AlkB subfamily of Fe(II)/ α -Ketoglutarate-dependent dioxygenases superfamily that has 9 members (ALKBH1-8 and FTO) in humans (Xu et al. 2014a). Enzymes of the ALKB family excise the methyl group through a two-step oxidative alkylation process and can act on DNA or RNA. Both FTO and ALKBH5 are found in nuclear speckles, suggesting that erasing of mRNA m⁶A is mostly nuclear (Jia et al. 2011; Zheng et al. 2013). In mice, loss of FTO leads to increased m⁶A levels and is associated with several metabolic disorders and cell differentiation (Zhoa et al. 2014), while loss of ALKBH5 also affects m⁶A levels and is characterized by impaired fertility resulting from spermatocyte apoptosis (Zheng et al. 2013). These findings indicate that these two demethylases function in different physiological processes and strongly suggest that they are crucial for the development and reproduction.

The Arabidopsis genome codes for thirteen proteins of the ALKB family, among which, based on sequence alignment, five (ALKBH9A, 9B, 9C, 10A, and 10B) are potential homologs of the mammalian ALKBH5 m⁶A-RNA demethylase

(Table 11.1; Mielecki et al. 2012; Duan et al. 2017). The Arabidopsis genome codes for a sixth putative homolog of human ALKBH5 (AtALKBH10C), but it is most likely not an active demethylase as it has a degenerate catalytic site (our unpublished data). Besides Arabidopsis, these enzymes can be found in agronomically important plants, for instance, the presence of *ALKB* demethylase orthologues was detected in *Nicotiana sylvestris* (Li et al. 2018), *Zea mays*, *Oryza sativa*, *Marchantia polymorpha*, and *Solanum lycopersicum*. No homolog of the FTO demethylase was found to exist in plant genomes (our unpublished data). Based on transcript level measurements, *ALKBH9B*, *9C*, and *10B* are the most expressed of all five Arabidopsis *ALKBH5* genes. Across development, it is always one (or few) of these three genes, whose transcript levels show the highest expression. In seedlings and leaves (juvenile, adult, and cauline), *ALKBH9B*, *9C*, and *10B* mRNAs show similar levels and are by far the most highly expressed genes. In buds and young siliques, *9B* and *10B* are almost the sole demethylases to be expressed and they show similar levels. Finally, *9B* is nearly the only demethylase expressed in the apical meristem and *10B* is by far the major eraser gene to be expressed in flowers and matured siliques. Recently, *in vitro* assays showed that *ALKBH9B* and *10B* have m⁶A-demethylase activities on RNA (Duan et al. 2017; Martínez-Pérez et al. 2017) and *10B* was shown to have a demethylase activity *in planta* on polyadenylated transcripts (Duan et al. 2017). *ALKBH10B*-mediated mRNA demethylation is required

[AUS]

t1.1 **Table 11.1** The Arabidopsis m⁶A modification regulatory system

| Function | Name | Arabidopsis locus | Mammalian homolog | Biological role | References |
|------------------------------|-----------------------|--------------------------|--------------------------------|--------------------------|------------------------------|
| mRNA m ⁶ A writer | MTA | AT4G10760 | METTL3 | Embryo development | Zhong et al. (2008) |
| | MTB | AT4G09980 | METTL14 | Embryo development | Bodi et al. (2012) |
| | FIP37 | AT3G54170 | WTAP | Meristem maintenance | Shen et al. (2016) |
| | VIRILIZER | AT3G05680 | KIAA1429 | Embryo development | Ruzicka et al. (2017) |
| | HAKAI | AT5G01160 | HAKAI | Embryo development | |
| mRNA m ⁶ A eraser | ^a ALKBH9A | AT1G48980 | ALKBH5 | – | Duan et al. (2017) |
| | ALKBH9B | AT2G17970 | ALKBH5 | Viral infection response | Martínez-Pérez et al. (2017) |
| | ^a ALKBH9C | AT4G36090 | ALKBH5 | – | Duan et al. (2017) |
| | ^a ALKBH10A | AT2G48080 | ALKBH5 | – | |
| | ALKBH10B | AT4G02940 | ALKBH5 | Flowering | |
| | <i>Name</i> | <i>Arabidopsis locus</i> | <i>YT512-B domain YTH-type</i> | <i>Biological role</i> | <i>References</i> |

(continued)

Table 11.1 (continued)

| Function | Name | Arabidopsis locus | Mammalian homolog | Biological role | References |
|--|-----------------------|-------------------|-------------------|--|--|
| t1.25 t1.26 YTH m ⁶ A readers | ^a ECT1 | AT3G03950 | YTHDF | Calcium-mediated signaling | Ok et al. (2005) |
| t1.27 t1.28 | ECT2 | AT3G13460 | YTHDF | Leaf and trichome morphogenesis | Scutenaire et al. (2018) |
| t1.29 t1.30 t1.31 | ECT3 | AT5G61020 | YTHDF | Leaf and trichome morphogenesis | Wei et al. (2018) Arribas-Hernández et al. 2018 |
| t1.32 t1.33 t1.36 t1.37 t1.38 | ECT4 | AT1G55500 | YTHDF | Leaf morphogenesis | Arribas-Hernández et al. 2018 |
| t1.39 t1.40 | ^a ECT5 | AT3G13060 | YTHDF | – | Ok et al. (2005) |
| t1.41 t1.42 t1.45 | ^a ECT6 | AT3G17330 | YTHDF | – | Scutenaire et al. (2018) |
| t1.46 | ^a ECT7 | AT1G48110 | YTHDF | – | |
| t1.47 | ^a ECT8 | AT1G79270 | YTHDF | – | |
| t1.48 | ^a ECT9 | AT1G27960 | YTHDF | – | |
| t1.49 | ^a ECT10 | AT5G58190 | YTHDF | – | |
| t1.50 | ^a ECT11 | AT1G09810 | YTHDF | – | |
| t1.51 t1.52 t1.53 t1.54 | ^a ECT12 | AT4G11970 | YTHDC | – | |
| t1.55 t1.56 t1.57 t1.58 | ^a CPSF30-L | AT1G30460 | YTHDC | ^b Nutrient uptake/oxidative stress response | Scutenaire et al. (2018) Li et al. (2017a, b) |

^aThese uncharacterized genes are potential players of m⁶A regulation

^bCPSF30-L isoform contains most of the short form polypeptide fused at its C-terminus with a canonical YTH domain of the DC-type; however, it is unknown if the biological role involves the m⁶A and the CPSF30-L reader function

for the proper transition from vegetative to reproductive stage. This is at least in part linked to the role of ALKBH10B in demethylating, in a timely manner, transcripts required for the floral transition and as a result stabilizing them (Duan et al. 2017). Arabidopsis ALKBH9B, was so far not found to affect m⁶A levels *in vivo*, but one cannot exclude the possibility that it works redundantly with other ALKBH5 orthologues, such as ALKBH9C. ALKBH9B was found to influence m⁶A abundance on the viral genome of Alfalfa mosaic virus (AMV) and regulate its infectivity (Martínez-Pérez et al. 2017).

It is important to note that the dynamic nature of m⁶A on mRNAs (e.g., the erasing of the m⁶A marks on mature cytoplasmic transcripts) is still highly debated in the scientific community (Rosa-Mercado et al. 2017). Nonetheless, mRNA demethylases were found to exist and to be evolutionarily conserved, their downregulation and overexpression shown to significantly alter the pattern of m⁶As on the polyadenylated transcriptome, and their loss to have drastic physiological impacts. Hence,

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255 they have roles to play in m⁶A-based post-transcriptional regulation, however,
256 where and how do they intervene remains to be understood.

257 **11.2.3 m⁶A Physiological, Cellular, and Molecular Roles**

258 The biological consequences of m⁶A methylation are multiple, but a common fea-
259 ture of most organisms is that it has pleiotropic physiological functions and is neces-
260 sary for reproduction, differentiation, growth, development, biotic and abiotic stress
261 responses. Arabidopsis is no exception to this. Except for HAKAI, loss-of-function
262 and hypomorphic mutants of any of the constituents of the plant writer complex
263 show total to drastic decrease of the levels of m⁶A on the polyadenylated transcrip-
264 tome and display identical phenotypes (Ruzicka et al. 2017). Complete loss of the
265 m⁶A mark results in embryogenesis defects leading to lethality of the embryos,
266 whose development is arrested at the globular stage (Vespa et al. 2004; Zhong et al.
267 2008; Bodi et al. 2012; Shen et al. 2016; Ruzicka et al. 2017). Downregulation of
268 N⁶-methyladenosines at post-embryonic stages has drastic pleiotropic consequences.
269 Plants show delayed growth and development with reduced apical dominance (Bodi
270 et al. 2012; Shen et al. 2016; Ruzicka et al. 2017). Seedlings with reduced levels of
271 m⁶A show an over proliferation of the vegetative shoot apical meristem (SAM),
272 accompanied by a dramatic delay in leaf emergence and aberrant leaf morphology
273 (Shen et al. 2016; Arribas-Hernández et al. 2018). Plantlets, with very low levels of
274 m⁶A, fail to develop a reproductive SAM and eventually die (Shen et al. 2016).
275 Hypomethylated plants also show trichome morphogenesis defects, with leaves
276 accumulating overbranched trichomes, due to abnormally high ploidy levels (Vespa
277 et al. 2004; Bodi et al. 2012; Scutenaire et al. 2018). Root growth and development
278 also require normal m⁶A levels. Indeed, hypomethylated mutants show reduced root
279 growth, aberrant gravitropic responses, abnormal root cap formation, and deficient
280 vascular development (linked to defective protoxylem development).

281 The m⁶A mark and its control is also most likely necessary not only for the
282 response of the plant to viral infection (Martínez-Pérez et al. 2017; Li et al. 2018)
283 but also for environmental growth conditions and stress exposure (Luo et al. 2014;
284 Anderson et al. 2018). In Arabidopsis, the viral RNA of AMV was found to have
285 m⁶A residues upon infection and to be demethylated *in vivo* by ALKBH9B
286 (Martínez-Pérez et al. 2017). Loss of ALKBH9B provokes a hypermethylation of
287 the viral RNA and downregulates AMV replication and infectivity. The current
288 model suggests that m⁶A could control AMV viral infection by signaling the viral
289 transcript to the nonsense mediated decay (NMD) pathway. This m⁶A-based
290 response to viral infection is likely not restricted to AMV (Martínez-Pérez et al.
291 2017), nor to Arabidopsis. Recently, a report by Li et al. (2018) correlated endoge-
292 nous m⁶A-levels to tobacco mosaic virus (TMV) infection in *N. tabacum*. Upon
293 infection, global m⁶A content decreased and the levels of transcripts coding for
294 putative homologs of ALBKH5 and MTA70 were, respectively, up- and downregu-
295 lated. These observations support a putative m⁶A-mediated control of viral infection

in tobacco as well. Methylome profiling of the transcriptomes of two *Arabidopsis* accessions [Can-0 (from Canary Islands) and Hen-16 (from Northern Sweden)] shows that most methylation peaks are shared by both ecotypes, supporting the crucial role of m⁶A-mediated regulation in development. Nonetheless, a portion of the detected methylated sites are specific to each ecotypes, and the presence of m⁶A correlates with highest expression levels of the marked genes. Considering the Can-0 and Hen-16 are originally from very distinct climates, one can postulate that m⁶A could play a role in plant acclimation to the environment (Luo et al. 2014). Along the same idea, a recent work by the Gregory lab (Anderson et al. 2018), profiled m⁶A on the transcriptome of salt treated *Arabidopsis* leaves and found that upon stress, transcripts coding for salt and osmotic stress response proteins gain m⁶A and are stabilized. This supports a role of m⁶A in promoting the plant response to stress, at least salinity.

Our understanding of the molecular and cellular bases of m⁶A physiological functions in plants is so far quite modest and limited to their role in the control of cytoplasmic mRNA stability (Luo et al. 2014; Shen et al. 2016; Duan et al. 2017; Wei et al. 2018; Anderson et al. 2018). At the global transcriptome scale, m⁶A acts to stabilize transcripts by preventing their endonucleolytic cleavage (4–5 nt upstream to the mark) and subsequent 5′-3′ digestion by XRN4, the plant homolog of XRN1 (Anderson et al. 2018). This is coherent with previous observations showing that the m⁶A mark correlates with elevated transcript levels (Luo et al. 2014). However, this is opposite to the situation in animals where the m⁶A mark is an mRNA-decay triggering signal at the global level (Ke et al. 2015, 2017). This transcriptome-wide observation does not stand for all *Arabidopsis* mRNAs, as there are cases where the presence of m⁶A directs a signal to turnover. Shen et al. (2016) found that the lack of m⁶A on two key SAM regulators (*WUSCHEL* and *SHOOTMERISTEMLESS*) prevents the timely degradation of their transcripts and proper regulation of SAM proliferation. Furthermore, ALKBH10B-mediated demethylation was found to stabilize transcripts of *FLOWERING LOCUS T (FT)*, *SPL3*, and *SPL9*, which are key regulators of the floral transition (Duan et al. 2017).

In animals, m⁶A also acts as a translation stimulatory signal, at transcriptome-wide level, and is known to control a handful of alternative splicing events (Lence et al. 2016; Haussmann et al. 2016), directs primary miRNA transcripts to processing (Alarcon et al. 2015), and acts directly on chromatin, where it contributes to DNA repair (Xiang et al. 2017) and to the XIST-dependent gene silencing (Patil et al. 2016). Whether m⁶A also acts on these processes in plants remains to be explored.

11.2.4 The Plant m⁶A Readers: YTH-domain-Containing Proteins

So far, only one type of m⁶A readers has been recognized in plants: those containing YTH domains. The Y^T521-B Homology domain (YTH) is a highly structured conserved RNA binding domain among eukaryotes. After being first identified as a

337 human splicing factor, YT521-B proteins carrying a YTH domain (now called
338 YTHDC1) were further identified and classified as DC type (YTH-domain-
339 containing protein) and DF type (YTH-domain family proteins), depending on the
340 subcellular localization (Imai et al. 1998; Hartmann et al. 1999; Stoilov et al. 2002;
341 Zhang et al. 2010). A recent analysis of YTH domains from yeast, metazoan and
342 Viridiplantae, found that they are of two evolutionary types: the DC-type group
343 comprising YTH domains of human YTHDC1 and 2 and the DF-type group con-
344 taining human YTHDF1-3 (Scutenaire et al. 2018).

345 The structural resolution of YTH domains from yeast and animal proteins showed
346 that both DC- and DF-type motifs adopt a conserved canonical fold of three
347 α -helices and six β -strands that creates an aromatic pocket (formed with three highly
348 conserved tryptophan residues) that tightly accommodates m⁶A (Li et al. 2014a, b; AUG
349 Luo and Tong 2014; Theler et al. 2014; Xu et al. 2014b; Zhu et al. 2014; Xu et al.
350 2015). Sequence comparisons support that the m⁶A-binding mode of the YTH
351 domains is largely conserved across eukaryotes (Scutenaire et al. 2018).

352 In plant genomes, genes coding for YTH-domain proteins experienced a large
353 expansion with thirteen genes in Arabidopsis (Table 11.1). Viridiplantae YTH-
354 proteins also carry DC- and DF-type domains that are further subdivided into two
355 (DCA and DCB) and three (DFA, DFB, and DFC) subgroups, respectively. This
356 observation suggests that plant YTH domain likely underwent neo-functionalization
357 and that they are not fully redundant (Scutenaire et al. 2018).

358 In plants, all the functional work done on YTH-domain m⁶A readers is from
359 Arabidopsis. Arabidopsis YTH domain was initially identified in two proteins found
360 to directly bind the CIPK1 (Calcineurin B-like-interacting protein kinase 1) calcium-
361 dependent kinase. Eleven proteins were found to share the YTH domain at their
362 C-terminus and called ECT1 to 11 (for evolutionarily conserved C-terminal region)
363 (Ok et al. 2005). Subsequent searches identified two additional proteins, which are
364 of the DC-type (while ECT1-11 is of DF-type): ECT12 of unknown function and
365 CPSF30-L, which is encoded by the long isoform of the gene encoding CPSF30, the
366 cleavage and polyadenylation subunit factor 30 (Addepalli and Hunt 2007).

367 The physiological and molecular roles of ECT proteins have been just recently
368 explored with the first functional analysis of a plant m⁶A reader, the Arabidopsis
369 ECT2 protein. *In vitro* and *in planta* assays showed that ECT2 binds to m⁶A-
370 containing RNAs and requires an intact aromatic pocket (Scutenaire et al. 2018; Wei
371 et al. 2018). *ECT2* transcript is the most abundant and ubiquitously expressed of all
372 ECTs, nonetheless, the pattern of expression of its protein is distinct (Scutenaire
373 et al. 2018; Wei et al. 2018; Arribas-Hernández et al. 2018). Consistently with its
374 expected role as m⁶A reader, *ect2* loss-of-function mutants, although not displaying
375 dramatic phenotypes, recapitulate some of the defects observed in hypomethylated
376 plants. First, ECT2 and its m⁶A-reading activity were found to be required for
377 proper trichome morphogenesis (Scutenaire et al. 2018; Wei et al. 2018; Arribas-
378 Hernández et al. 2018). In the absence of ECT2, or the sole presence of a mutant
379 allele coding for a protein with a mutated aromatic pocket, trichomes are over-
380 branched—a phenotype that arises from increased ploidy levels. ECT3 was also
381 found to be required for normal trichome morphogenesis, acting together (but not

redundantly) with ECT2. ECT2 and ECT3 were also found to act redundantly to ensure the timely emergence and proper leaf formation. This role also requires their m⁶A reading activities (Arribas-Hernández et al. 2018). Leaf morphogenesis also requires ECT4 but solely in backgrounds where both ECT2 and ECT3 are absent.

The loss of ECT2 induces the rapid downregulation, through degradation, of three trichome-morphogenesis transcripts (*TTG1*, *ITB1*, and *DIS2*) that carry m⁶A. This observation is consistent with the role of ECT2 as m⁶A reader, as in its absence, the m⁶A-signal is likely improperly decoded and transcripts targeted for degradation. Furthermore, it also suggests that aberrant trichome morphogenesis could be, at least in part, the consequence of the improper expression of these three transcripts (Wei et al. 2018).

In planta, ECT2 accumulates mostly in the cytoplasm, but is also found in the nucleus. Upon stress-induced downregulation of translation initiation (heat and osmotic stress), ECT2 relocates to stress granules, which are messenger ribonucleoprotein particles (mRNPs) triage and storage centers, also containing factors of the translation machinery. The formation of cytoplasmic foci upon stress is also a feature of ECT4, but not ECT3, which is coherent with the presence in ECT2 and ECT4 (but not ECT3) of YPQ-rich regions, reminiscent of that found in human YTHDF proteins and aggregation-prone factors. The dynamic and complex subcellular distribution of these readers suggests that they might decode the m⁶A signal in several post-transcriptional processes, such as splicing/maturation and/or nucleocytoplasmic export step.

11.3 The m⁵C Epitranscriptomic Mark in Plants 404

Compared to m⁶A modification, m⁵C is less abundant and much less research has been conducted so far. Transcriptome-wide m⁵C represents 0.4% of the total number of cytosines on human polyadenylated transcripts (Squires et al. 2012), whereas m⁶A represents 1–1.5% of the adenosines on mRNA (Ke et al. 2015). This cytosine methylation mark is widespread and mainly detected in tRNAs and rRNAs, affecting RNA conformational structure and translational process (Chow et al. 2007; Motorin and Helm 2010; Squires and Preiss 2010), but it was also identified in mRNAs and noncoding RNAs (Squires et al. 2012). Consensus sequence for m⁵C sites has been distinguished in Archaea, and until recently, none were found in animal and plant species (Edelheit et al. 2013). However, two enriched sequence motifs around m⁵C sites were recently detected in Arabidopsis, with the most significantly enriched motif at the consensus HACCR (where H = U > A > C and R = A/G) (Cui et al. 2017). Additionally to the consensus motif, David et al. (2017) suggested that RNA secondary structure may also be important to confer methylation at m⁵C sites, by demonstrating that a 50-nucleotide sequence flanking at m⁵C site is essential for methylation in a transient expression system in *N. benthamiana* (David et al. 2017).

The Arabidopsis transcriptome-wide profiling of m⁵C-containing RNAs has been recently mapped by two distinct approaches. First, David et al. (2017) identified

423 more than a thousand m⁵C sites in mRNAs, lncRNAs, and sRNAs by RNA bisulfite
424 sequencing, using several tissues and RNA methyltransferase mutants. Quantitative
425 differences in methylated sites between roots, shoots, and siliques revealed a
426 dynamic pattern to suggest a tissue-specific function of m⁵C modification (David
427 et al. 2017). The second approach, using RNA immunoprecipitation followed by
428 deep-sequencing, also revealed a tissue-specific regulation of m⁵C in various tissues
429 and at different developmental stages (Cui et al. 2017). Thousands of m⁵C sites were
430 found to be enriched around start and stop codons of thousands of expressed genes
431 in young seedlings (Cui et al. 2017).

432 Two classes m⁵C writer proteins were identified in eukaryotes, the transfer RNA
433 aspartic acid methyltransferase 1 (TRDMT1) [also known as DNA methyltransferase
434 2 (DNMT2)] found in yeast, plants, and animals (Goll et al. 2006; Burgess et al.
435 2015), and the yeast tRNA specific methyltransferase 4 (TRM4) [also known as the
436 human NOP2/Sun domain protein 2 (NSUN2)] (Motorin and Grosjean 1999;
437 Auxilien et al. 2012). The Arabidopsis genome encodes eight potential m⁵C
438 methyltransferases, two are the TRM4-like proteins, TRM4A and TRM4B (Chen
439 et al. 2010; Cui et al. 2017), from which the latter has been already characterized in
440 plants (David et al. 2017; Cui et al. 2017). Further analysis was undertaken, using
441 loss-of-function mutants for the tRNA-specific m⁵C methyltransferase (TRM4B),
442 revealing that m⁵C modification is required for proper root development and oxidative
443 stress responses. David et al. (2017) observed defects in primary root elongation
444 due to impaired cell division at the meristematic tissue, and showed that loss of
445 TRM4B increases sensitivity to oxidative stress and decreases tRNA stability.
446 Accordingly, Cui et al. (2017) showed that TRM4B loss-of-function mutants exhibit
447 downregulation of key genes of root development, namely *SHORT HYPOCOTYL 2*
448 (*SHY2*) and *INDOLE ACETIC ACID-INDUCED PROTEIN 16 (IAA16)*, which is
449 positively correlated with the stability and m⁵C modification in their transcripts (Cui
450 et al. 2017).

451 Together, these studies identified the m⁵C modification as another important
452 methylation mark on RNA that has an impact on plant development and adaptive
453 responses. Further research is needed to elucidate the mechanisms and functional
454 roles of m⁵C-mediated regulation of protein-coding genes, and to perhaps identify
455 potential m⁵C readers and erasers. A recent study showing that an Arabidopsis RRM
456 motif-containing ALY protein preferentially binds to an m⁵C-modified RNA (Pfaff
457 et al. 2018) has encouraged future research efforts on this potential m⁵C reader.
458 Arabidopsis ALY protein family functions on mRNA export, and *aly* mutant plants
459 exhibited various defects in vegetative and reproductive development, including
460 shorter primary roots, altered flower morphology and reduced seed production
461 (Pfaff et al. 2018). Altogether, it seems that the m⁵C modification may influence
462 protein-coding genes with widespread consequences for the development and stress
463 responses.

11.4 Concluding Remarks

464

The advances of new technologies, such as sequencing-based transcriptome-wide mapping, revolutionized the field of RNA chemical modifications and permitted to unveil a novel layer in the control of gene expression that is now known as epitranscriptomics or RNA epigenetics. Advances on animal epitranscriptomic regulation have been dazzling in the past years and several epitranscriptomic marks (including m^1A , m^5C , m^6A , m^6Am , ac^4C , or h^5mC) have been mapped transcriptome-wide in different cell types and environmental conditions. We learned from animal studies the crucial importance of these regulatory marks that control constitutive cellular processes and allow their reprogramming to permit organism development and acclimation. In plants, our current understanding of epitranscriptomics is limited to the m^6A and m^5C -based regulations in a single model plant. Nonetheless, Arabidopsis studies revealed that in plants also these modifications are crucial to growth and acclimation. It is hence now a necessity to foster more knowledge on this novel field of biology in model, but also in cultivated plants.

A first step is to get a global vision of the nature and patterning of chemical modifications on the polyadenylated transcriptome of plants. With the advent of global approaches such as LC-MS/MS or next-generation sequencing, one is now capable of not only knowing the nature and relative abundance of mRNA modifications but also to decipher their distribution on each expressed genes. Such repertoires might easily be obtained from diverse species, organs, environmental conditions, and even populations. We anticipate these data to give insights on the role and agronomical importance of RNA epigenetics, as did, for example, the 1001 Arabidopsis epigenomes. Analyses and comparisons of these repertoires will give us clues regarding the interplay that exists between the various marks or their respective importance in acclimation and growth.

Of course, several fundamental questions remain to be addressed in model plants that will contribute to our understanding of the importance of RNA epigenetics in crop development and resistance to stressful conditions, encountered in cultivated fields. What are the actors (writers, readers, and erasers) of the different epitranscriptomic mark-based regulations? Understanding the molecular, cellular, and physiological roles of these actors will help comprehend the role of the mark and the interplay between marks. As an example, data already obtained from Arabidopsis studies on the features and role of the m^6A mark can be exploited to understand the importance of this mark in cultivated species. With the advent of genome editing technologies, reverse genetic approaches on proteins of the writer complex, m^6A -readers, and erasers can easily be conducted.

RNA epigenetics in animals is no longer an emerging field but a fast growing new topic of biology that appeals to more and more scientists. Of course, several deficiencies in the epitranscriptomic control of gene expression were linked to cancers and diseases. In plants, the m^6A mark controls development at the embryonic and post-embryonic stages, and very likely required for defense against viral infections and stress responses. The community of plant scientists interested in RNA

507 epigenetics is so far quite small and must grow to foster sufficient knowledge to
 508 understand this novel extremely complex field of biology.

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