A tale of two morphs: developmental patterns and mechanisms of seed coat differentiation in the dimorphic diaspore model Aethionema arabicum (Brassicaceae)

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SUMMARY

The developmental transition from a fertilized ovule to a dispersed diaspore (seed or fruit) involves complex differentiation processes of the ovule’s integuments leading to the diversity in mature seed coat structures in angiosperms. In this study, comparative imaging and transcriptome analysis were combined to investigate the morph-specific developmental differences during outer seed coat differentiation and mucilage production in Aethionema arabicum, the Brassicaceae model for diaspore dimorphism. One of the intriguing adaptations of this species is the production and dispersal of morphologically distinct, mucilaginous and non-mucilaginous diaspores from the same plant (dimorphism). The dehiscent fruit morph programme producing multiple mucilaginous seed diaspores was used as the default trait combination, similar to Arabidopsis thaliana, and was compared with the indehiscent fruit morph programme leading to non-mucilaginous diaspores. Synchrotron-based radiation X-ray tomographic microscopy revealed a co-ordinated framework of morph-specific early changes in internal anatomy of developing A. arabicum gynoecia including seed abortion in the indehiscent programme and mucilage production by the mucilaginous seed coat. The associated comparative analysis of the gene expression patterns revealed that the unique seed coat dimorphism of Ae. arabicum provides an excellent model system for comparative study of the control of epidermal cell differentiation and mucilage biosynthesis by the mucilage transcription factor cascade and their downstream cell wall and mucilage remodelling genes. Elucidating the underlying molecular framework of the dimorphic diaspore syndrome is key to understanding differential regulation of bet-hedging survival strategies in challenging environments, timely in the face of global climatic change.

Keywords: Aethionema arabicum, bet-hedging, developmental anatomy, diaspore dimorphism, fruit development, phenotypic plasticity, reproductive development, seed coat mucilage, synchrotron radiation X-ray tomographic microscopy, transcription factors.

INTRODUCTION

Fruit and seed development represent a crucial phase of angiosperm reproduction. The transition from the flower after pollination into the diversity of mature dispersal units, i.e., fruits and seeds (diaspores), is particularly important for annual plant species whose life-cycle is entirely dependent on successful diaspore production,
dispersal and regeneration from seed (Baskin and Baskin, 2014; Finch-Savage and Leubner-Metzger, 2006; Linkies et al., 2010; Roeder and Yanofsky, 2006; Walck et al., 2011). Diaspore development in many plant model systems, including Arabidopsis thaliana, is monomorphic, i.e., only a single type (morph) of fruit and/or seed is produced. The default monomorphic ‘bauplan’ within the Brassicaceae is the development of dehiscent fruits (DEH) containing mucilaginous seeds (M’). A. thaliana and Lepidium sativum as examples (Ferrandiz M, 1999; Mühlhausen et al., 2013; Scheler et al., 2015). The DEH/M’ fruit/seed programme leads to fruit valve opening to release mature M’ seeds as diaspores, which upon imbibition release mucilage from their outer seed coats (myxospermy) (Viuades et al., 2020; Western, 2012; Yang et al., 2012). Mutations in A. thaliana fruit development genes, such as the bHLH (basic helix-loop-helix) transcription factor (TF) INDEHISCENT and the MADS-box TFs SHATTERPROOF1/2 (SHP1/2), block fruit valve opening which phenotypically result in indehiscent fruits (IND) (Mühlhausen et al., 2013). In their phenotype, these mutants resemble species in which the IND fruits themselves serve as diaspores, i.e., the dispersal units are seeds encased by the fruit wall (pericarp). Fruit development in monomorphic species with IND fruits, such as Lepidium appelianum, is caused by reduced expression of these and other TFs of the dehiscence network.

Likewise, in many A. thaliana mutants, outer seed coat (testa) differentiation and mucilage production are impaired in TF genes such as NAC-REGULATED SEED MORPHOLOGY1 and 2 [NARS1/2; plant-specific TFs of the NAC (NAM, ATAF and CUC) family], GLABRA2 (GL2; a homeodomain TF), MYB61, SHP1/2 and SEEDSTICK (STK; MADS-box TFs), or in downstream cell-wall remodelling protein (CWRP) genes (Golz et al., 2018; Voiniciuc et al., 2015; Western, 2012). Seeds of the mucilage-modified (mum) mutants fail either to release mucilage (mum1, mum2), to produce reduced quantities (mum4), or to have altered adherence of mucilage (mum3). Coupled with the development of either DEH or IND fruits is the development of seeds from fertilized ovules and the differentiation of the seed coat from the ovule integuments. In A. thaliana the two layers of the outer integument develop into the mucilage-accumulating testa and the three layers of the inner integument into the endothelium (Golz et al., 2018; Voiniciuc et al., 2015; Western, 2012). Upon imbition of mature seeds, mucilage is extruded from the outer cell walls of mucilaginous cells in the testa. The testa epidermis and its mucilage secretory cells exhibit significant anatomical diversity also of taxonomic value within the Brassicaceae (Vaughan et al., 1971). The main ecological adaptation of mucilaginous seed coats may be in facilitating imbition and maintenance of moisture for growth in water-deficient environments, as well as in aiding or restricting diaspore dispersal (Arshad et al., 2019; Baskin et al., 2014; Gutterman, 2000; Western, 2012; Yang et al., 2012).

Understanding how new morphologies, organs or body plans arise is one of the most fascinating questions in evolutionary developmental (evo-devo) plant biology. In contrast to monomorphic species, which produce only a single fruit and seed morph (monodiaspory), several angiosperm families independently evolved heteromorphism, characterized by the production of two or more distinct fruit and seed morphs (heterodiaspory) on individual plants (Baskin and Baskin, 2014; Baskin et al., 2014; Imbert, 2002). The resultant heteromorphic diaspores differ in their morphological and physiological properties including size, shape, colour, dispersal, dormancy, germination and mucilage production upon imbibition (Arshad et al., 2019; Baskin et al., 2014; Lenser et al., 2016; Lu et al., 2015; Wang et al., 2020; Yang et al., 2015). These heteromorphic diaspore traits have been proposed to be an adaptive bet-hedging strategy to cope with spatiotemporally variable environments (Baskin et al., 2014; Imbert, 2002), but very little is known about the underpinning mechanisms governing diaspore development into distinct morphs. A deep understanding of heteromorphism at the phenotypic level is crucial for molecular studies and is hampered in many heteromorphic systems by the high number of morphs, production of intermediate morphs and lack of a published genome sequence.

Here, we exploit the fruit and seed dimorphism in Aethionema arabicum (Figure 1), an annual member of the earliest diverging sister tribe (Aethionemaeae) within the Brassicaceae (Lenser et al., 2016; Mohammadin et al., 2017), to investigate early morph-transitioning by advanced 3D imaging [synchrotron-based radiation X-ray tomographic microscopy (SRXTM)] and transcriptome analysis. Two distinct morphs of fruits and seeds are produced on the same individual infructescence (Figure 1a). DEH fruits release four to six non-deep dormant, mucilaginous (M’) seeds. The surface of the dry mature M’ seed coat is visible as an array of compressed, large circular-hexagonal cell outlines with thickened cell walls, representing mucilage-producing, conical papillae, which are irreversibly extruded upon seed imbibition (Figure 1b). In contrast, IND fruits each contain a single, pericarp-imposed deep dormant non-mucilaginous (M’) seed (Figure 1b). No intermediate fruit or morphs are produced (Lenser et al., 2016). While the multiple-seeded DEH fruits are predominantly produced on main flowering branches, single-seeded IND fruits in contrast are favoured on higher-order side branches (Lenser et al., 2018). The strict dimorphism, together with available genome and transcriptome sequences (Fernandez-Pozo et al., 2021; Nguyen et al., 2019) (Wilhelmsson et al., 2019), make Ae. arabicum an excellent model system for investigating the mechanisms of diaspore dimorphism.
RESULTS AND DISCUSSION

Co-ordinated time-course of Aethionema arabicum fruit and seed development reveals early initiation of morph-specific changes in seed coat differentiation

To establish key developmental events during the transition from flower bud to dimorphic fruit, a sequential account of the structural formation of reproductive organs in *Ae. arabicum* is provided (Figure 1c) by reference to the post-fertilization stages of *A. thaliana* gynoecium development (Ferrandiz et al., 1999; Roeder and Yanofsky, 2006). In *Ae. arabicum*, fruit development follows a comparable pattern at initial stages from primordial bud formation to floral morphogenesis (Figure 1c). The lack of visible morph-specific external differences at the bud and early flower stage makes comparative analysis of *Ae. arabicum* morph differentiation difficult. To overcome the experimental problem that during the initiation of distinct morph differentiation to discriminate morphologically between the DEH and IND morphs may not yet be possible visually, we took advantage of the fact that fruit morphs are not distributed evenly throughout the plant (Lenser et al., 2016, 2018). These earlier publications demonstrated that >95% of fruits produced on second-order branches of undisturbed plants are IND morphs, and that 95% of fruits produced on the main branch of plants where the side branches are constantly removed are DEH morphs. This established experimental approach was used in our work for the imaging and the RNA-sequencing (RNA-seq) sampling. To verify the molecular results of the RNA-seq experiment, we used reverse transcription–quantitative polymerase chain reaction (RT-qPCR) with the same approach for the IND sampling, but for the DEH sampling we harvested from the undisturbed main branch across multiple plants. In this independent RT-qPCR experiment with independent biological RNA samples we combined this with expanding the time course to 3 and 10 days after pollination (DAP) at which the morphs are visibly distinct (Figure 1). Together this provided verification of the identified gene expression patterns in independent experiments and a detailed coverage of the early stages of morph separation.

Figure 1 and Figure S1 show that to the point of anthesis (0 DAP), morphologies of flowers that would later produce DEH and IND fruits appeared phenotypically identical. Analysis of pollen showed no difference between morphs (Figure S2), and aniline blue-stained pollen tubes show no

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difference in growth (Lenser et al., 2018). While petals and sepals readily abscised from the IND morph at 3–4 DAP, perianth withering in the DEH morph did not occur until 6 DAP, despite initiation of lateral fruit elongation (Figure 1c). Thus, floral development until very early stages of gynoecium expansion appears phenotypically monomorphic from the outside. Beyond this, fruits became clearly dimorphic in their development when pericarp tissue began expansion at 5 DAP. Comparison of fruit maturation patterns showed that onset of DEH silicle yellowing (37 DAP) was approximately 7 days earlier than in the IND fruit morph (43 DAP). This is consistent with earlier work comparing the transcriptomes of Ae. arabicum dry seeds, which indicated that M⁺ seeds may desiccate earlier and mature faster compared with M⁻ seeds (Wilhelmsson et al., 2019). Thus, fruit maturation into a dispersal-ready propagule also seemingly occurred at a faster rate for the DEH morph (Figure 1c). This time-course therefore allowed the identification of externally visible key events before, and soon after, phenotypic morph separation.

To explore the internal anatomy underlying the morph-specific phenotypic changes, we performed comparative SRXTM during the time-course of DEH and IND reproductive development. SRXTM is non-destructive and has been used successfully to reveal cryptic features and internal structures of modern and fossil flowers, fruits and seeds (Arshad et al., 2020; Friis et al., 2014; Smith et al., 2009a). Reconstructed digital sections of Ae. arabicum obtained by SRXTM provided excellent cell and tissue details (Figure S1). Floral buds (0 DAP) exhibited a morphologically well-structured gynoecium and immature stamens. Ovules at anthesis (0 DAP) in both DEH (Figure S1f) and IND (Figure S1g) morphs exhibit differentiated internal structures of an identical nature. External morphologies of the bud (Figure S1a,d) and flower at 1 DAP (Figure S2e,h) were also consistently monomorphic in their anatomy. Within early immature fruits (approximately 7 DAP), clear external and internal differences between the two seed morphs were visible (Figure S1i–n); DEH fruits possessed four to six fertilized ovules (developing M⁺ seeds), while IND fruits possessed only one (developing M⁻ seeds). Therefore, the comparative SRXTM imaging revealed that dimorphic fruits considerably differed in the early initiation of distinct seed coat development of their M⁺ (within DEH fruits) and M⁻ (within IND fruits) seed morphs.

**Dimorphic changes to the ovule wall and seed abortion are early post-fertilization processes**

A temporal histological analysis of isolated gynoecia post-fertilization development indicated the more exact timing of changes to the wall of the ovules within developing fruits (Figure S3). The asymmetric growth of a single seed within IND fruits pushed the septum towards the side of the opposing seed chamber at 2–3 DAP, seemingly resulting in the rupture of the septum and ‘fusion’ of the two locules (Figure S3f). The inner integument at 0–3 DAP consisted of multiple layers of parenchymatous cells during early seed development (Figure S3a–f), but later appeared as one or two layers of crushed palisade cells (Figure S3g–j). By 5 DAP, outer integuments had started differentiation into mucilage secretory cells in M⁺ seeds only. Thus, the observed morphological changes associated with the transition of the integuments into the mature seed coat indicate that, at the same time as external differences between morphs become visible at 2–3 DAP, the developmental programme guiding seed coat mucilage development also becomes morph-specific. Consistent with earlier work demonstrating that seed abortion becomes visible in flowers at 2 DAP (Lenser et al., 2018), we observed seed abortion in 2–3 DAP flowers of the IND programme (Figure S3f), demonstrating that it is a very early post-fertilization event. Together with the distinct morphological changes in seed coat development, this implies that the distinct molecular programmes driving Ae. arabicum seed and fruit dimorphism may be initiated very early in flowers upon fertilization.

**Comparative RNA-seq analyses reveal transcriptomic differences during early morph-transitioning**

For the transcriptome analysis, the described local separation of the fruit morph programmes allowed direct morph-specific comparisons during reproductive development by collecting bud (0 DAP), flower (1 DAP) and fruit (30 DAP) samples from the distinct branches representing the DEH fruit (M⁺ seed) and the IND fruit (M⁻ seed) programmes, for which the RNA-seq analysis was conducted (Data S1). Replicate RNA-seq samples clustered tightly by organ (Figure 2a) and by morph (Figure 2b), as observed in a principal components analysis (PCA). The majority of the variability in the data was explained by PC1 (67.2%), while PC2 and PC3 explained 22.6% and 4.8% respectively, and clustering of samples for each stage separately demonstrating that early flower samples are much more distinct compared with bud samples (Figure 2c). An unsupervised hierarchical clustering approach based on Euclidean distance measures, also revealed the high similarity of bud samples from DEH and IND morphs (Figure 2d). However, while flower samples also clustered by morph, these samples were more similar in their transcriptional profile to bud samples than to fruit samples. These results suggest that the developmental trajectory of Ae. arabicum morphs is strongly evident from their transcriptional profile at the post-fertilization flower stage, but not at the bud stage of development.

Morph-specific analysis of differentially expressed genes (DEGs) detected significant differences at the three harvested stages (Figure 3). In total, 16 243 genes were found to be differentially expressed in IND versus DEH samples...
The highest number of morph-specific DEGs were found at the flower (1 DAP) stage (in total, 4482 regulated at least 2-fold between DEH and IND, 2380 upregulated and 2102 downregulated; Figure 3). In contrast to this, fewer DEGs were identified at the bud (0 DAP, 240 DEGs) and immature fruit (30 DAP, 2022 DEGs) stages (Figure 3). Interestingly, >8% of the 4482 flower DEGs were TFs and other...
master regulators interacting with TFs and RNA polymerase II to drive the morph-specific changes in fruit and seed (including ovule abortion in the IND programme) development observed (Figures 1 and 4; Figures S1 and S3). Analysis of gene ontology (GO) terms associated with up- and downregulated transcripts, showed significantly over- and under-represented GO terms of each class (molecular function and biological process; Data S2). Morph-specific GO comparison at the flower stage using Fisher’s exact test, revealed for example that in the IND upregulated molecular function output list GO:0003700 (DNA-binding TF activity) was no. 3 and GO:0140110 (transcription regulator activity) was no. 5 with a false discovery rate corrected \( P < 0.0001 \) (Data S2). To investigate further the morph-specific role of mechanisms that control the transcription of genes we conducted motif enrichment analysis and compared it with the DEG results obtained for the different TF classes.

To analyse our *Ae. arabicum* datasets for motif enrichment we used the Analysis of Motif Enrichment tool of the MEME Suite (http://alternate.meme-suite.org/tools/ame) (McLeay and Bailey, 2010). Fisher’s exact statistical test \( (P < 0.01, \text{E value threshold } 10) \) with comparison against the Arabidopsis DAP v1 database identified relatively enriched motifs (Data S3). Flower datasets delivered 331 enriched motifs, a higher number compared with the bud and fruit datasets (Data S3). The morph-specific enrichment in NAC, bZIP (basic leucine zipper), HD (homeodomain), AP2/EREBP (APETALA2/ethylene-responsive element binding proteins), C2H2 (C2H2 zinc finger), C2C2 (C2C2 zinc finger) and MYB-related promoter motifs indicate that these may be key targets of TFs in morph-specific processes; examples for identified bZIP, NAC, WRKY, HD and AP2/EREBP enriched motifs are presented in Figure S4. To analyse the expression patterns of TFs in the *Ae. arabicum* RNA-seq datasets we identified TFs using the Plant TF database PnTFDB (Perez-Rodriguez et al., 2010; Wilhelmsson et al., 2017). This analysis identified 1552 *Ae. arabicum* TFs of which 366 were differentially expressed in IND flower samples (Figure S4), almost all of the 27 WRKY-related promoter motifs (Data S3, Figure S4) in *Ae. arabicum* IND flowers, in comparison with DEH samples (developing multiple M° seeds). Though IND transcript abundances showed considerable variation in the flower (1 DAP), expression levels showed a dramatic morph-specific difference at 3 DAP, where *AearMEE14* and *AearMEE59* expression correlates well with the timing of ovule abortion as observed by histology (Figure 4; Figure S3). It is known from work in *A. thaliana* that MEE14 encodes the central cell guidance-binding protein1 (CBP1), which acts as a mediator of transcription initiation in a complex with RNA polymerase II and TFs during fertilization (Li et al., 2015). As in *Ae. arabicum* three ovules within the IND fruit are aborted at an early zygotic stage approximately 2–3 days post-fertilization, we speculate that AearCBP1 through interaction with TFs may play a role in this highly morph-specific co-ordinated process.

Interestingly, several of the *A. thaliana* MEE mutants have lesions in TF genes of the WRKY, MYB and TCP families (Pagnussat et al., 2005). That we see an enrichment in WRKY- and MYB-, and TCP-related promoter motifs (Data S3, Figure S4) in *Ae. arabicum* IND flowers, in comparison with DEH flowers, may indicate that the corresponding TFs are key components in morph-specific processes during ovule abortion, and early seed and fruit development.

Almost all TFs associated with early morph-transitioning are upregulated in the IND programme

Consistent with the enrichment in WRKY-related promoter motifs (Figure S4), almost all of the 27 *Ae. arabicum* WRKY TF DEGs were upregulated in IND flower samples (Figure 4c). This upregulation at 1 DAP was 2–9-fold and two groups can be distinguished according to the expression patterns in immature fruits: the transcript abundances of 16 WRKY TF DEGs upregulated in IND flower samples (group A) were decreased to equal levels in fruit samples (Figure S5) suggesting that they play major roles in early morph-specific processes. An example for this is *AearWRKY28* (Figure 4c) for which the *A. thaliana* orthologue is known as a key component in ovule development with this co-ordinated process preceding single M° seed development. Forward genetic screens in *A. thaliana* identified genes involved in female gametogenesis and early embryo development, highlighting several maternal effect embryo arrest (MEE) mutants associated with defects in embryo sac development, fertilization and early embryogenesis (Pagnussat et al., 2005). Of the nine identified MEE orthologues in *Ae. arabicum*, the *AearMEE14* and *AearMEE59* showed an increase in transcript abundances specifically within IND flower samples (Figure 5a). The approximately 9- and 2-fold increase, respectively, detected from normalized RNA-seq data was further investigated by RT-qPCR using independently grown samples at higher temporal resolution (Figure 5b). Interestingly, a time-dependent increase in expression was consistent for IND samples (developing a single M° seed) in comparison with DEH samples (developing multiple M° seeds). Though IND transcript abundances showed considerable variation in the flower (1 DAP), expression levels showed a dramatic morph-specific difference at 3 DAP, where *AearMEE14* and *AearMEE59* expression correlates well with the timing of ovule abortion as observed by histology (Figure 4; Figure S3). It is known from work in *A. thaliana* that MEE14 encodes the central cell guidance-binding protein1 (CBP1), which acts as a mediator of transcription initiation in a complex with RNA polymerase II and TFs during fertilization (Li et al., 2015). As in *Ae. arabicum* three ovules within the IND fruit are aborted at an early zygotic stage approximately 2–3 days post-fertilization, we speculate that AearCBP1 through interaction with TFs may play a role in this highly morph-specific co-ordinated process.

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Figure 4. Differentially expressed transcription factor (TF) genes associated with morph-specific anatomical changes in the development of dehiscent (DEH) and indehiscent (IND) *Aethionema arabicum* fruits.

(a) Morph transition from a flower into a DEH or IND fruit is coupled with a multitude of gynoecial changes associated with the ovules, carpels, septum and pericarp tissue, as well as morph-specific early anatomical differences in early seed coat development. These changes lead to the development of non-deepdormant, mucilaginous (M+) seeds in DEH fruits, and the pericarp-imposed deep dormant, single non-mucilaginous (M-/C0) seed in IND fruits. Shown are 6-µm thick longitudinal sections of fruits at approximately 5 days after pollination (DAP), stained with toluidine blue. Scale bars = 300 µm. Shown are synchrotron-based radiation X-ray tomographic microscopy (SRXTM) images of M+ (left) and M-/C0 (right) seeds at approximately 7 DAP (see Figure S1 for detailed description of SRXTM). Scale bars = 75 µm; E, embryo; SC, seed coat.

(b) Overview of differential expression (> 2-fold; \( P = 0.05 \)) of TFs; see Data S4 for details and expression values using the complete set of TFs of the PlnTFDB (Perez-Rodriguez et al., 2010; Wilhelmsson et al., 2017).

(c) Examples for TF differentially expressed genes in DEH and IND bud (0 DAP), flower (1 DAP) and fruit (30 DAP) samples. Mean ± SE are presented. For gene names see main text.

(d) Transcript analysis of the BRC1/HD-ZIP/NCED cascade, which in *Arabidopsis thaliana* leads to abscisic acid (ABA) accumulation (Gonzalez-Grando et al., 2017) and in *Ae. arabicum* differs between the morphs in that it is specifically upregulated in the IND programme.
(Zhao et al., 2018). The transcript abundances of the other 10 WRKY TF DEGs upregulated in IND flower samples (group B) were upregulated in DEH fruit samples, an example for this is AearWRKY40 (Figure S5) for which the A. thaliana orthologue is known to be involved in responses to abscisic acid (ABA) (Ahmad et al., 2019b). Interestingly, seed abortion in Davidia involucrata trees was associated with increased expression of most WRKY and MYB TFs (Li et al., 2016). Likewise, 37 of the 46 A. arabicum MYB TF DEGs were upregulated in IND flower samples (Figure 4b). An example of these is AearMYB101, for which the A. thaliana orthologue is a key component in the fertilization process (Liang et al., 2013), AearMYB101 transcript abundances were 7-fold in IND versus DEH flower samples (Figure 4c). The NAC-domain TFs NAC046 and NAC087 are implicated in the developmentally controlled cell death in A. thaliana seedling root caps (Huysmans et al., 2018). The observed 10- and 7-fold higher expression of AearNAC46 and AearNAC87, respectively (Figure 4c); therefore, suggests they have roles in post-fertilization ovule abortion within IND fruits. Other A. arabicum NAC (Figures S4 and S5) and MYB TF DEGs in flower samples include NARS1/2 and MYB61 (Figure 6) known to be master regulators in mucilage deposition in A. thaliana outer seed coat development (Golz et al., 2018; Kunieda et al., 2008; Penfield et al., 2001; Voiniciuc et al., 2015; Western, 2012).

Members of the plant-specific B3-domain (ABI3/VP1; ABA INSENSITIVE/VP1/ABI3-LIKE3) superfamily of TFs which are upregulated in A. arabicum IND flower samples include AearABS2/AearNGAL1 (Figure 4c) and AearVAL3 (Figure S5). Overexpression of ABNORMAL SHOOT2/NGATHA-LIKE1 (ABS2/NGAL1) in A. thaliana leads to an early loss of flower petals (Shao et al., 2012). In agreement with this, the 5-fold upregulation of AearABS2/AearNGAL1 in A. arabicum IND flower samples (Figure 4c) is associated with an earlier loss of petals in IND fruits compared with DEH fruits (Figure 1c). Transcripts of VP1/ABI3-LIKE3 (VAL3) and other B3-domain TFs are more strongly expressed in seedless grape cultivars (compared with seed-containing cultivars) and have been proposed to be involved in seed abortion and development seedlessness (Ahmad et al., 2019a). In agreement with a possible role of AearVAL3 in post-fertilization ovule abortion within IND fruits, its transcript abundances are approximately 2.5-fold higher in IND compared with DEH flower samples (Figure S5). An example for a B3-domain TF, which is stronger
expressed in DEH (approximately 4-fold) compared with IND flower samples is AearVDD (Figure 4c). Silencing of the VERDANDI (VDD) gene leads to defects in fertilization and semi-sterility in A. thaliana (Matias-Hernandez et al., 2010). These authors also showed that VERDANDI is the direct target of the MADS-domain TF SEEDSTICK (STK). A missense mutation in the grapevine orthologue of A. thaliana STK is associated with seed abortion leading to seedlessness in cultivated grapevine (Royo et al., 2018). Transcript abundances of AearSTK are approximately 2.5-fold higher in IND compared with DEH flower samples (Figure 6). SEEDSTICK is a master regulator with many roles, including specifying ovule identity, fruit growth and septum fusion, seed coat development and mucilage production (Di Marzo et al., 2020; Ezquer et al., 2016; Golz et al., 2018).

Homeodomain leucine zipper and ABA-related basic zipper TFs associated with early morph-specific seed and fruit development

Previous work with Ae. arabicum used RT-qPCR to reveal that the TEOSINTE BRANCHED1, CYCLOIDEA, PCF (TCP) TF BRANCHED1 (BRC1), known to be a branching repressor, has a 7-fold increased transcript abundance in IND samples as compared with DEH samples at the early flower stage (Lenser et al., 2018), which we confirmed here for AearBRC1 expression in the RNA-seq data (Figure S5). Together with increased auxin and cytokinin contents at the early flower stage BRC1 was proposed to be part of the molecular mechanisms for fruit morph decision (Lenser et al., 2018). Interestingly, also the ABA contents increased 3-fold at the Ae. arabicum early stage in IND samples as compared with DEH samples. ABA accumulation and signalling is known as a hallmark of seed and bud dormancy (Finch-Savage and Leubner-Metzger, 2006; Gonzalez-Grandio et al., 2017). Consistent with the deeper dormancy of Ae. arabicum M+ seeds and IND fruit diaspores as compared with the readily germinating M− seeds, the increased ABA contents are maintained throughout the IND programme from early flowers to mature diaspores (Arshad et al., 2019; Lenser et al., 2016, 2018). ABA signalling inside A. thaliana buds is controlled by a TF cascade in which BRC1 binds to and positively regulates the transcription of three homeodomain leucine zipper protein (HD-ZIP)-encoding genes HOMEBOX PROTEIN 21 (HB21), HB40 and HB53, which leads to enhanced expression of the ABA biosynthesis gene 9-cis-EPOXYCAROTENOID DIOXIGENASE 3 (NCED3) and consequently to ABA accumulation (Gonzalez-Grandio et al., 2017). We show here that the BRC1/HD-ZIP/NCED cascade is also evident in Ae. arabicum in the IND programme: AearHB21, AearHB40, AearHB53 and AearNCED transcript abundances were higher specifically at 1 and 3 DAP in IND samples compared with DEH samples (Figure 4d). Phylogenetic analysis revealed that Ae. arabicum has two AearNCED3 genes (Figure S6) and four of the six AearNCED were higher expressed in IND flower samples leading to 3-fold higher overall AearNCED transcript abundance at 1 DAP (Figure 4d). Seedlessness, ovule development and embryo abortion in grapes was also associated with enhanced expression of HD-ZIP TFs. Among the specifically upregulated TF genes in seedless grape cultivars was VvHDZ09, which clusters very closely together with A. thaliana HB21, HB40 and HB53 in the phylogenetic analysis (Li et al., 2017).

Gonzalez-Grandio et al. (2017) also demonstrated that among the downstream TFs induced by the BRC1/HD-ZIP/NCED cascade and the ABA accumulation are NAC TFs such as NAC-LIKE, ACTIVATED BY AP3/PT (NAP) and ABA-dependent bZIP TFs such as ABA RESPONSIVE ELEMENT (ABRE)-BINDING FACTOR3 (ABF3) and G-BOX BINDING FACTOR3 (GBF3). Consistent with a role of ABA-dependent TFs in early IND-morph development, transcripts of AearABF3 (Figure 4d), AearGBF3 and several other bZIP (Figure S5) TFs accumulate in IND flower samples. The same pattern is evident for AearNAP and several other NAC TFs (Figure S5). Together with HD-ZIP TFs, these ABA-dependent bZIP and NAC TFs are known to be master regulators in drought, heat, cold and salt stress responses as well as in secondary cell wall synthesis (Diao et al., 2020; Hwang et al., 2019; Taylor-Teeples et al., 2015). As for the NAC and WRKY TFs, also most of the AP2-ERPBPs and heat shock factor TF DEGs were upregulated in Ae. arabicum IND flower samples (Figure S5). The AP2-ERPBPs are involved in regulating secondary cell wall synthesis (Taylor-Teeples et al., 2015) and, as the heat shock factors, in abiotic stress responses (Guo et al., 2016; Mizoi et al., 2012). That 73% of the Ae. arabicum TF DEGs are upregulated in IND as compared with DEH flower samples is a characteristic for most or all of the TF families (Figure 4b). An important exception are the bHLH family TF DEGs for which examples in flower samples (Figure S5) include the IND-upregulated DEFECTIVE REGION OF POLLEN1 (DROP1) known to be involved in fertilization (Zhang et al., 2017), as well as the DEH-upregulated INDEHSICENT gene required for fruit valve opening (Mühlhausen et al., 2013).

TF cascades and distinct downstream mucilage-related gene expression during morph-specific outer seed coat differentiation

Seed integuments showed considerable morph-specific seed coat development. Seed integuments showed considerable morph-specific seed coat differentiation already at approximately 7 DAP (Figure 4a), namely in the development and secretion of mucilage between the outer primary wall and the proplast (in a ring around the area where starch granules are located within the cell) in developing M+ seeds (in DEH fruits). This secretion resulted in a ring-shaped mucilage pocket (Figure 4a; arrowhead). In contrast to this, the developing M−
seed coat (in IND fruits) comprised a more distinct, inner epidermal layer as well as several outer cell layers undergoing differentiation within the outer integument (Figure 4a). At approximately 40 DAP, the outermost epidermal layer formed large mucilage secretory cells in the case of mucilaginous seeds (M−) from the DEH fruit morph (Figure S1p,q), but a thin outer epidermal layer lacking mucilage secretory cells in the single (M+) seed (Figure S1r,s) of the IND fruit. Only several collapsed cell layers and an inner integument of relatively thick-walled cells remained in the developed and more differentiated M− seed coat (Figure S1r). As both the SRXTM and histological approaches demonstrated key differences in patterns of mucilage synthesis and seed coat epidermis (SCE) development (Figure 4a; Figures S1 and S3), we hypothesized that the transcriptional network underpinning seed coat development in the M− seed programme may be altered in a morph-specific manner as compared with the M+ seed programme. The Ae. arabicum M− seed programme leads to a mucilaginous seed coat with polysaccharide cell wall-like structures with large amounts of pectin combined with cellulose and hemicelluloses based on what is known from *A. thaliana* SCE development (Golz et al., 2018; Voiniciuc et al., 2015; Western, 2012).

Figure 6 depicts the three-tier SCE TF cascade known from *A. thaliana* and presents the comparative gene expression patterns from *Ae. arabicum* master regulators and exemplary downstream cell-wall remodelling genes. The RNA-seq data for the upper tier SCE TF (Figure 6a) revealed that the expression patterns of NARS1/NAC2, NARS2/NAM and the APETALA2 (AP2) floral homeotic gene, differ between the two morphs. The NAC TF *AearNARS1/AearNARS2* was expressed roughly equally in buds (‘B’, 0 DAP), but were higher in IND flower samples (M− seeds) as compared with DEH flower samples (M+ seeds) (‘F’, 1 DAP). NARS1/2 are master regulators of *A. thaliana* embryogenesis and the development of the outer integument. They are expressed in the outer seed coat, knock-out mutation and overexpression both lead to defects in outer seed coat development and mucilage deposition (Kunieda et al., 2008). The *Ae. arabicum* RNA-seq demonstrated that in contrast to *AearNARS1/2* and *AearAP2*, TFs of the MYB-bHLH-WD40 (MWB) complex (Golz et al., 2018; Vioutes et al., 2020; Voiniciuc et al., 2015) did not show a morph-specific expression difference in flower samples (Figure 6a). Analysis of *AearAP2* and *AearNARS2* gene expression by RT-qPCR at 1, 3 and 10 DAP (Figure 6b) not only confirmed that the transcript abundances differ at the flower stage (1 DAP), but also during all the subsequent early stages of seed coat differentiation, particularly at 3 DAP. The upper-tier mucilage regulatory network (AP2, NARS1/NAC2, MWB complex) modulates the activity and expression of the middle-tier TFs (Figure 6a) to control outer seed coat differentiation and mucilage production (Golz et al., 2018; Vioutes et al., 2020; Voiniciuc et al., 2015).

AP2 and the MWB complex are required for the expression of the HD-ZIP TF GLABRA2 (GL2) and the WRKY TF TRANSPARENT TESTA GLABRA2 (TTG2), both of which act in the early stages of integument and epidermal cell differentiation (Golz et al., 2018; Vioutes et al., 2020; Voiniciuc et al., 2015). Consistent with the finding that *Ae. arabicum* M− seed coat programme is associated with altered seed coat development and reduced mucilage production (Figure 1; Figure S1), the RNA-seq data revealed a reduced induction of *AearGL2* expression IND flower samples (M− seeds) as compared with DEH flower samples (M+ seeds) (Figure 6a). RT-qPCR analysis (Figure 6b) demonstrated that this expression difference becomes even more pronounced at 3 and 10 DAP at which *AearGL2* is highly expressed in association with the M− seed coat programme leading to mucilage production and low in the M+ seed coat programme leading to non-mucilaginous seeds. Higher transcript abundance of the middle-tier MYB61 TF was evident in *Ae. arabicum* IND flower samples (Figure 6a). RT-qPCR verification showed for *AearMYB61* that this ratio shifts from being expressed higher in IND samples at 3 DAP to being expressed higher in DEH samples at 10 DAP (Figure 6b). In contrast to MYB61, the expression pattern for MYB52 did not differ (Figure 6a,b). Seeds of *A. thaliana* loss-of-function mutants in AP2, GL2, TTG2, MYB61 and MYB52 fail to release mucilage upon hydration due to a lack in mucilage secretory cell differentiation or defects in mucilage and columella production in the seed coat (Penfield et al., 2001; Western, 2012; Western et al., 2004). Several of these TFs are also involved in secondary cell wall formation, abiotic stress and ABA signalling. The middle-tier TFs, GL2, MYB61 and MYB52, control the activity of lower-tier TFs, including the MADS-box TF SEED-STICK (STK) and SHATTERPROOF1/2 (SHP1/2) (Figure 6). *AearSTK* and *AearSHP1* gene expression is upregulated in IND samples (M− seed programme) during the early stages, while it remains low in DEH samples (Figure 6). These TF are required for seed coat development and determine the mechanical properties of the seed coat (Ehlers et al., 2016; Ezquer et al., 2016; Golz et al., 2018). Seeds of *A. thaliana* stk mutants release only small amounts of mucilage and have altered cellulose-pectin matrixes of their cell walls.

The mucilage regulatory network of TF controls the expression of downstream genes involved in outer seed coat differentiation and mucilage production and modification (Golz et al., 2018; Vioutes et al., 2020; Voiniciuc et al., 2015; Western, 2012). Prime targets include cellulose, hemicellulose and pectin biosynthesis, as well as pectin secretion and methylesterification. Two distinct and structured domains (layers) of extruded seed mucilage can be distinguished. In *A. thaliana* an inner adherent mucilage
layer is tightly associated with the seed and contains crystalline cellulose, hemicellulose, and as pectins rhamnogalacturonan I (RGII), homogalacturonan with differing degrees of methylesterification. In contrast to this, the outer water-soluble layer is almost exclusively composed of RGII pectin. Mucilage is modified and its extrusion is reduced or lacking in the MUCILAGE-MODIFIED1-5 (MUM1-5) mutants. In this aspect they resemble Ae. arabicum M- seeds, which exhibit significantly reduced mucilage extrusion (Figure 1b) and lack the conical papillae of M+ seeds (Lenser et al., 2016). Ruthenium red (revealing the inner adherent mucilage layer) and methylene blue (highlighting columellae and cellulose rays) staining demonstrated that all components, including the cellulose rays for columella biosynthesis, are affected in M- seeds (Figure 1b). In agreement with a reduction in cellulose biosynthesis, CELLULOSE SYNTHASE (CESA) gene expression was severely reduced during Ae. arabicum M- seed coat development. The transcript abundances for AearCESA2 and AearCESEAS/AearMUM3 are 2-8-fold lower in 3-10 DAP M- seeds as compared with M+ seeds (Figure 6d). The STK TF is upregulated in the Ae. arabicum M- seed programme (Figure 6c), and is, consistent with the reduced AearCESA2 expression, known in A. thaliana to inhibit CESA2 expression directly (Ezquer et al., 2016). Mucilage extrusion of A. thaliana cesa5/mum3 seeds is reduced and lacks a structured adherent layer with reduced cellulose content (Sullivan et al., 2011). These authors showed that CESA5 is specifically expressed in the outer seed coat and the cellulose is required for anchoring the pectin components of mucilage to the seed.

PECTIN METHYLESTERASE (PME) and PME-INHIBITOR (PMEI) genes play crucial roles in seeds and mucilage properties with the PME16 gene being specifically expressed in the outer seed coat to modify pectin properties (Ezquer et al., 2016; Golz et al., 2018; Saez-Aguayo et al., 2013; Scheler et al., 2015; Voiniciuc et al., 2015). Mucilage release is delayed in A. thaliana pmei6 mutants by increased methylesterification of the pectin homogalacturonan component. Several TFs including GL2, STK and MUM1/LUH are known to control PMEI gene expression, with reduced expression of PMEI6 in the A. thaliana gl2 mutant. The transcript abundance for AearPMEI6 is approximately 2.5-fold lower in 10 DAP M- seeds as compared with M+ seeds (Figure 6d). Biosynthesis of the pectin RGI component requires the RHAMNOSE BIOSYNTHESIS2 (RH2/MUM4) gene for which the A. thaliana rhm2/mum4 mutant has severely reduced mucilage production (Usadel et al., 2004; Western, 2012; Western et al., 2004). Several TFs, including GL2 and MYB61, are known to control RH2/MUM4 gene expression and the production of RGI (Arsovski et al., 2009; Penfield et al., 2001). The transcript abundance for AearRH2/AearMUM4 is lower in 1-10 DAP M- seeds as compared with M+ seeds (Figure 6d).

Consistent with a role of AearGL2 in the reduced AearRH2/AearMUM4 and AearPMEI6 expression, it is also expressed at reduced level in the M- seeds programme (Figure 6a). GL2, MYB61, STK, MUM1/LUH and other TFs also control GALACTURONOSYLTRANSFERASE-LIKE5 (GATL5), β-GALACTOSIDASE6 (βGAL6/MUM2) and other pectin-modifying genes (Golz et al., 2018; Viudes et al., 2020; Voiniciuc et al., 2015; Western, 2012). Their differential expression may further contribute to the reduced production and modified properties of the Ae. arabicum M- seed coat mucilage (Figure 1; Figures S1 and S6).

CELLULOSE SYNTHASE-LIKE A2 (CSLA2) is involved in the biosynthesis of galactomannan, a hemicellulosic polysaccharide in mucilage (Voiniciuc et al., 2015). Mucilage of A. thaliana csla2 mutant seeds is modified resulting in a more compact adherence layer and an altered spatial organization and reduced content of crystalline cellulose; and natural variation of A. thaliana seed mucilage was found to be associated with its differential expression (Voiniciuc et al., 2016; Yu et al., 2014). AearCSLA2 expression differed between the M- and M+ seed programme (Figure 6d) supporting the view that a complex morph-specific control by the Ae. arabicum transcriptional network affects all the mucilage polysaccharide components.

**Aethionema arabicum as a dimorphic model for SCE development and differentiation in mucilage production**

The external surface of seed and fruit coats is extremely diverse, reflecting the multiple adaptations to environmental conditions. Upon imbibition of water, the diaspores of many species extrude mucilage from the outer seed coat (myxospermy) or fruit coat (myxocarp) for which the adaptive value has attracted the attention of plant ecologists (Viudes et al., 2020; Western, 2012; Yang et al., 2012). The diaspore mucilage is typically composed of cellulose, pectin and hemicellulosic polysaccharides, but ‘true slimes’ lacking cellulose are also known with flax seeds as an emerging model. Myxospermic Brassicaceae seeds, including A. thaliana, L. sativum and Ae. arabicum M- seeds produce and extrude cellulosic mucilage in which crystalline cellulose provides structure and prevents mucilage from being washed away (Lenser et al., 2016; Scheler et al., 2015; Vaughan et al., 1971; Western, 2012; Yang et al., 2012). On the molecular level a set of A. thaliana (mucilage-modified) mutants has served to identify the mucilage TF network cascade and its downstream CWRP genes. The sequential evolution of myxodiapory is evident from both the interspecies and intraspecies variability in these mucilage TFs and CWRPs expressed during outer seed coat development and mucilage secretory cell differentiation. Conserved TF cascades and CWRP genes were evident from a transcriptome analysis of Artemisia sparocephala fruit coat mucilage biosynthesis, an example for a
myxocarpic species adapted to desert conditions (Han et al., 2020; Yang et al., 2011). We demonstrate here that Ae. arabicum provides an excellent dimorphic model system for SCE development in which the M+ seeds resemble the ‘default’ myxospermy pathway (as in the A. thaliana system) and the development of the non-mucilaginous M− seed and IND fruit represent the non-myxospermic and non-myxocarpic pathways, respectively.

The advantage of the Ae. arabicum system is that the comparative molecular developmental pathways of myxospermy (M+ seeds) and non-myxospermy (IND fruits containing M− seeds) can be studied on the same plant. For some TFs the reduced expression in the IND/M+ seed programme resembles the reduced mucilage production in A. thaliana mum mutants. The TF cascades combined with the SRXTM imaging also demonstrate that morph-specific developmental programmes are initiated very early post-fertilization. They were manifested by distinct expression patterns of master regulators and immediately followed by the expression of downstream genes leading to morph-specific developmental changes including the seed abortion in the IND/M− programme and the distinct differentiation of mucilage production between the two morphs. The Ae. arabicum diaspore dimorphism is a blend of phenotypic plasticity and bet-hedging, two evolutionary modes of response to environmental variance (Arshad et al., 2020; Arshad et al., 2019; Bhattacharya et al., 2019; Lenser et al., 2016, 2018; Mohammadin et al., 2017; Wilhelmsson et al., 2019). A sequential evolution of the mucilage-associated TF and CWRP genes is evident in seed plants with natural variability within families, species and accessions, including in the Brassicaceae (Viudes et al., 2020). Seed myxospermy is an advanced trait with an origin that may provide an excellent dimorphic model system for SCE development in which the M+ seeds resemble the ‘default’ myxospermy pathway (as in the A. thaliana system) and the development of the non-mucilaginous M− seed and IND fruit represent the non-myxospermic and non-myxocarpic pathways, respectively.

SRXTM and classical microscopy of reproductive development

Five replicate buds, flowers, immature (approximately 7–10 DAP) fruits and mature (approximately 40 DAP) fruits were fixed in 3% glutaraldehyde plus 4% formaldehyde in 0.1 M piperase/N,N-bis (2-ethanesulfonic acid) (PIPEs) buffer at pH 7.2. Samples were then rinsed with 0.1 M PIPEs, and dehydrated in five changes of EtOH (30%, 50%, 70%, 95%, 100%). Critical point drying was performed on samples (Balzers CPD-030; Bal-Tec, Schalksmühle, Germany) that were then mounted on to 3 mm diameter brass pin stubs using two-component epoxy (Araldite®; Huntsman Advanced Materials GmbH, Basel, Switzerland) and imaged at the TOMCAT beamline of the Swiss Light Source, Paul Scherrer Institute, Villigen, Switzerland (Stampanoni et al., 2006). Data were acquired using a 10× objective and an sCMOS camera (PCO.edge; PCO, Kelheim, Germany), with an exposure time of 80 ms at 12 keV. Projections were post-processed and reconstructed using a Fourier-based algorithm (Marone and Stampanoni, 2012). Tomographic slice data derived from the scans were analysed using Avizo® 9.5.0 (Thermo Scientific™; Visualization Science Group Inc., Burlington, MA, USA) for Windows 10 Pro 64-bit, and contrast adjusted in Adobe Photoshop Lightroom CC as described (Arshad et al., 2020). Details of whole seed staining and microscopical analysis of seed coat differentiation are described in Supporting Information.

RNA-seq and molecular analyses of transcriptome data

Floral buds (0 DAP), flowers at anthesis (1 DAP) and immature fruits at their full length (30 DAP, before the onset of yellowing and drying) were harvested from second-order branches of plants that grew undisturbed (IND) or from the main branch of plants where side branches were constantly removed during development (DEH), as previously described by Lenser et al. (2019). Details of the extraction, quality control, processing and sequencing of four biological replicate RNA samples using 50-bp single-end mode on Illumina® Hiseq 2000 Analyzers are described in the Supporting Information. Data trimming, filtering, read mapping and feature counting, was as previously described (Wilhelmsson et al., 2019); the details for this are also described in the Supporting Information. DEGs were identified using an adjusted P-value (false discovery rate) cut-off for optimizing the independent filtering set to 0.05 (Data S1). Details for the GO, promoter motif analyses (McLeay and Bailey, 2010) are described in the Supporting Information. Sequence data from A. arabicum are available in the CoGe database (https://genomévolution.org/coge/) under the following genome ID: v2.5, id33988.

Gene expression analysis via RT-qPCR

Floral buds (0 DAP), and flowers at 1, 3 and 10 DAP were harvested from second-order branches (IND) or from the main branch (DEH) of multiple undisturbed plants. Tissue was frozen in liquid nitrogen, and ground using a Precellys® 24 tissue homogenizer (Bertin Instruments, Montigny-le-Bretonneux, France). RNA was extracted using methods described for RNA-seq. The quantity and purity of RNA was determined using an Agilent 2100 Bioanalyzer with the RNA 6000 Nano Kit (Agilent Technologies, Santa Clara, CA, USA), using the 2100 Expert Software to calculate RNA Integrity Number (RIN) values. One microgram of DNase I-treated RNA was used for cDNA synthesis with random hexamer primers, using the Invitrogen™ SuperScript™ III First-Strand Synthesis System (ThermoFisher Scientific, Waltham, MA USA). RT-qPCR

EXPERIMENTAL PROCEDURES

Plant material and experimental growth conditions

Plants of Aethionema arabicum (L.) Andrz. ex DC. were grown from accession no. ES1020 (Lenser et al., 2018), in Levington compost with added horticultural grade sand (F2 + S), under long-day conditions (16 h light/20°C and 8 h dark/18°C) in a greenhouse as described (Lenser et al., 2018). The DAP was defined phenotypically as the time at which the flowers open (anthesis) and the four long stamens extend over the gynoecium.

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reactions were performed in a CFX96 Touch™ Real-Time PCR Detection System (Bio-Rad, Watford, UK), using ABIstep qPCR SYBR Green Mix (ThermoFisher Scientific) and primer pairs listed in Table S1, with the following parameters: 95°C for 15 min, 40 cycles with 95°C for 15 sec, and 60°C for 30 sec, and 72°C for 30 sec, then 65°C for 30 sec. Melt-curve analysis verified the absence of primer-dimer artefacts and amplification of a single product from each qPCR assay. PCR efficiencies and Cq values were calculated using Real-time PCR Miner algorithm using raw fluorescence data as input (Graber et al., 2011). The geometric mean of A. arabicum orthologues of ADAPTIN FAMILY PROTEIN (AearCMSP, AA44G00404), CALCINEURIN-LIKE METALLO-PHOSPHOESTERASE SUPERFAMILY PROTEIN (AearCMSP, AA10G00283), and the unknown protein AA19G00315 (AearAA19G00315) was used as reference for normalization. All RT-qPCR experiments were performed using five independent biological replicates. Statistical analysis was performed using GraphPad Prism (v.7.0a; San Diego, CA, USA), using a two-way ANOVA with a post-hoc correction for multiple comparisons.

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AUTHOR CONTRIBUTIONS
WA, TL, GT, TS, SAR and GL-M conceptualized and designed the research. WA, TL, JO, TS and FM performed experiments. WA, TL, PKIW, JOC, TS, MEC, WS, FM, MP and GL-M analysed and interpreted data. WA and GL-M wrote the original manuscript draft. All authors commented on the draft and were thereby involved in shaping the manuscript. All authors reviewed and approved the final version of the manuscript.

CONFLICT OF INTEREST
The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT
Single-ended Illumina raw reads from this study were uploaded to the NCBI Sequence Read Archive (SRA) and can be found under BioProject PRJNA639786 (https://www.ncbi.nlm.nih.gov/bioproject?term=PRJNA639786). The mapping data were uploaded to the Comparative genomics platform CoGe under ‘Fruit development’ experiments accompanying the v2.5 genome (https://genomesevolution.org/coge/GenomeInfo.pl?gid=28950).

SUPPORTING INFORMATION
Additional Supporting Information may be found in the online version of this article.

Figure S1. SRXTM imaging of Aethionema arabicum fruit morph development.

Figure S2. Scanning electron microscopy of Ae. arabicum pollen.

Figure S3. Morph-specific ovule anatomy of Ae. arabicum.

Figure S4. Analysis of motif enrichment in Ae. arabicum gene promoters.

Figure S5. Morph-specific differential expression of transcription factors.

Figure S6. Phylogenetic analysis of Ae. arabicum CCD genes.

Table S1. RT-qPCR primer sequences.

Data S1. Supporting data file with RNA-seq expression results.

Data S2. Supporting data file GO analysis.

Data S3. Supporting data file Enriched Motif Analysis.

Data S4. Supporting data file expression data for TF DEGs.

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