

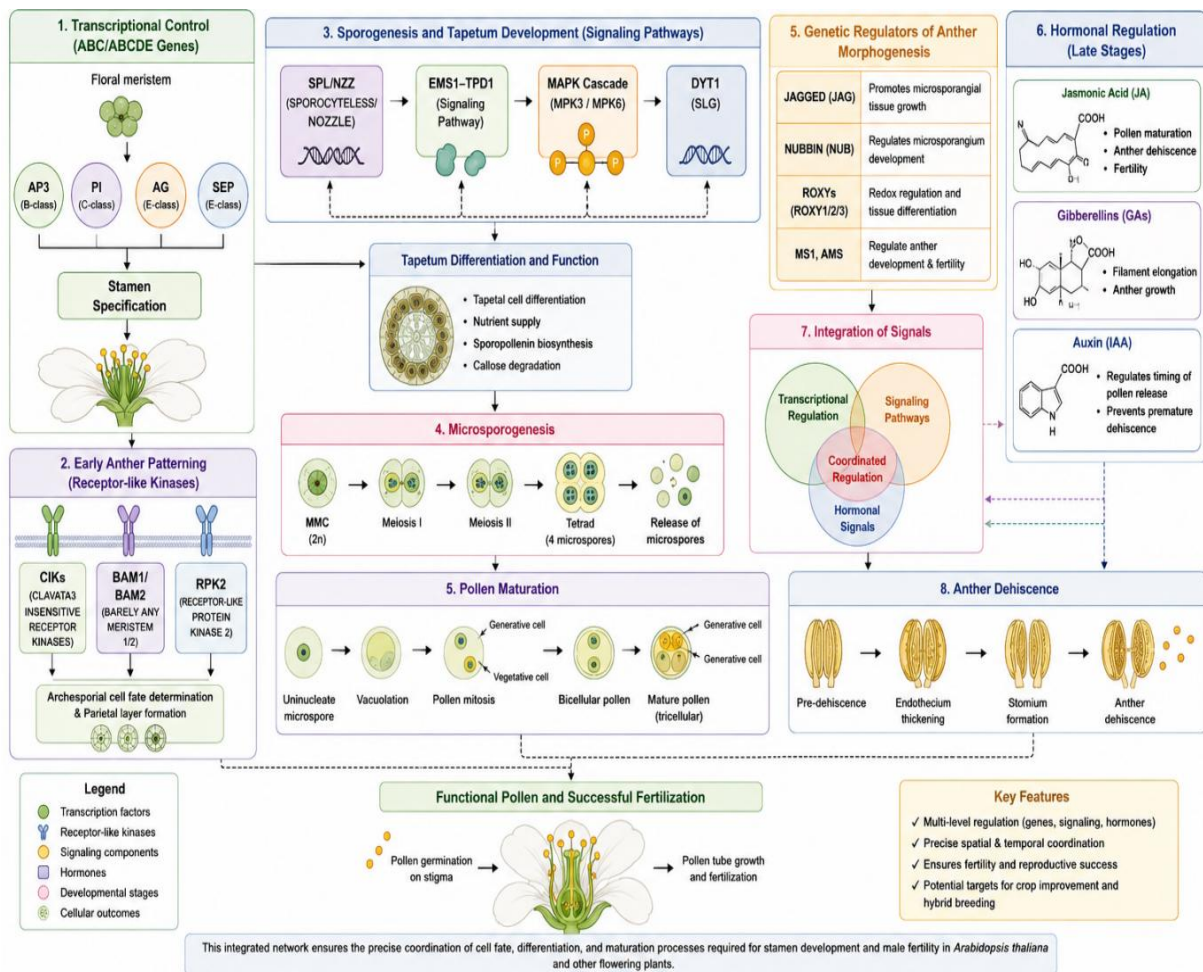


Figure 2 Integrated regulatory network governing anther development, pollen maturation, and male fertility in flowering plants

Image caption: The figure illustrates the coordinated regulation of male reproductive development by transcription factors, receptor-like kinases, signaling pathways, and phytohormones. Early anther patterning is regulated by *CIKs*, *BAM1/BAM2*, and *RPK2*, followed by activation of *SPL/NZZ*, *EMS1-TPD1*, MAP kinase signaling, and additional regulators controlling tapetum differentiation and microsporogenesis. Hormonal pathways involving jasmonic acid, gibberellins, and auxin regulate pollen maturation, filament elongation, and anther dehiscence. The integration of these molecular networks ensures successful pollen development, fertilization, and male fertility, providing potential targets for functional genomics, hybrid breeding, genome editing, and crop improvement

The staged progression of anther development in *Arabidopsis thaliana* provides a valuable model for dissecting the cellular and molecular mechanisms underlying male reproductive development. Early events, particularly archisporial cell specification and parietal layer formation, are tightly regulated by receptor-like kinases such as *CIKs*, *BAM1/2*, and *RPK2* (Hord et al., 2006; Mizuno et al., 2007; Cui et al., 2018). The phenotypic similarities observed in higher-order mutants suggest that these kinases operate within interconnected signaling pathways to maintain stem cell homeostasis and ensure proper tissue differentiation (Albrecht et al., 2005; Hu et al., 2018). Their interaction and phosphorylation dynamics further emphasize the importance of signal transduction in early anther patterning.

Transcriptional regulators such as *SPOROCTELESS/NOZZLE* (*SPL/NZZ*) play a pivotal role in initiating sporogenesis, acting downstream of floral identity genes (Yang et al., 1999; Ito et al., 2004). In parallel, the *EMS1-TPD1* signaling module and MAP kinase pathways (*MPK3/MPK6*) are essential for tapetum differentiation and function (Jia et al., 2008; Zhao et al., 2017). The tapetum emerges as a critical tissue, not only supporting pollen development but also influencing fertility outcomes, as evidenced by numerous mutants exhibiting male sterility due to tapetal defects (Zhang et al., 2006; Zhang and Yang, 2014). These findings reinforce the concept that successful microsporogenesis depends on precise coordination between sporogenous and somatic tissues.