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Special Issue Editorial

Seed biology: the birth of plant life

This Special Issue addresses how seed germination and early establishment are being reshaped by climate change, integrating advances in signaling, metabolism, seed structures, and seed technologies. It highlights recent conceptual and methodological breakthroughs that move the field from embryo-centric and stress-at-germination views toward an integrated, multi-tissue and life cycle perspective with direct relevance for crop resilience.

Ongoing climate change is projected to induce profound societal disruptions, with food security among the most immediate and high risks due to increasing heat extremes, drought, and rainfall variability that affect crop productivity and yield stability (IPCC, 2022). In that context, seeds are critical points for adaptation, because they condition the very first steps of plant establishment. They sustain plant reproduction and underpin food and feed production systems, from farmer-saved seed lots to industrial seed supply chains. They integrate developmental history and environmental information, shaping stand establishment and yield potential through traits such as germination timing, uniformity, and seedling vigor. Over the last decade, seed vigor has increasingly been framed as an agronomic trait central to sustainable crop production, particularly under variable environments (Reed *et al.*, 2022; Bailly and Gomez-Roldan, 2023).

The most immediate and intuitive link between seeds and climate change concerns the impact of environmental stress at germination. Heat, water deficit, salinity, and fluctuating conditions often delay or desynchronize emergence, leading to poor crop establishment and yield losses. For this reason, germination under stress has long been the first focus when addressing seed responses to climate change. Over the past 10–20 years, extensive research has significantly advanced this field, extending classical abscisic acid (ABA)/gibberellic acid (GA)-centered models toward integrated molecular frameworks that incorporate stress physiology and metabolism, and clarifying how environmental cues modulate germination decisions (Née *et al.*, 2017; Carrera-Castaño *et al.*, 2020). Importantly, it is now increasingly evident that germination performance is not determined only at sowing. The long seed development phase on the mother plant, often occurring during summer, is itself highly vulnerable to prolonged heat and hydric fluctuations. An expanding literature demonstrates that the maternal environment programs germination phenology, dormancy at harvest, and seed vigor, meaning that climate stress can imprint seeds before they ever encounter the soil (Penfield and MacGregor, 2017; Reed *et al.*, 2022; Brunel-Muguet *et al.*, 2025). These advances have coincided with a deeper appreciation of seed compartment specialization. Germination is no longer viewed as an embryo-only process: the endosperm and seed coat (testa) are active determinants of dormancy, signaling, and mechanical restraint, interacting with hormonal and metabolic networks in a tissue-specific manner (Piskurewicz *et al.*, 2023).

In this Special Issue, we therefore highlight major dimensions of germination research that are particularly relevant in a changing climate: (i) germination signaling and metabolism controlling the germination transition to climate-related stresses and variability; (ii) emerging tools and techniques to assess and improve germination performance under fluctuating environments; and (iii) new insights from tissue-level (embryo/endosperm/seed coat) perspectives that refine mechanistic understanding and open up routes for translation.

Molecular, signaling, and metabolic control of seed biology in a changing environment

miRNAs are now recognized as key post-transcriptional regulators of gene expression, governing essential developmental processes and mediating plant adaptation to environmental stresses (Abbas *et al.*, 2022). Boccaccini *et al.* (2026) comprehensively synthesized and systematized current knowledge on miRNA-mediated regulatory networks in rice, with particular emphasis on reproductive development, seed formation, germination, and seed longevity. Across these processes, hormonal signaling pathways and cell proliferation emerge as the primary targets of miRNA action. Given the detrimental effects of abiotic stresses on global rice productivity, the review further integrates climate change-related perspectives, highlighting the potential of miRNA-based regulatory insights for developing targeted strategies to enhance crop resilience under changing environmental conditions.

The study of Miray *et al.* (2026) makes an original contribution to current knowledge on seed maturation by moving beyond the Arabidopsis-centered view of storage compound accumulation and examining a wild, stress-adapted *Brassicaceae* species, *Cakile maritima*, in an ecologically relevant context. The discovery of markedly different fatty acid compositions between embryo and endosperm adds a new layer of complexity to our understanding of seed reserve partitioning. Particularly innovative is the demonstration that environmental temperature exerts contrasting effects on polyunsaturated fatty acid accumulation in the embryo and endosperm, challenging the assumption that environmental regulation of seed reserves operates uniformly across seed tissues. In a broader context of seed development, dormancy, and germination, these findings reinforce the view that zygotic tissues are independently regulated yet functionally coordinated units.

Tian *et al.* (2026) present a clear advance in our understanding of seed germination regulation by TEOSINTE BRANCHED1/CYCLOIDEA/PROLIFERATING CELL FACTOR (TCP) transcription factors. By identifying TCP8 as a negative regulator of seed germination, they extend the current paradigm, which had previously positioned Class I TCPs (most notably TCP14 and TCP15) as exclusively positive regulators of this process. The characterization of the *tcp8.1* mutant links reduced primary dormancy with altered ABA- and GA-related gene expression, providing a mechanistic basis for the observed germination phenotype. In addition, the suppression of both single-mutant phenotypes in the *tcp8.1 tcp14.4* double mutant provides strong evidence for antagonistic functions of TCP8 and TCP14. The demonstration that TCP8 counteracts the function of its close homolog TCP14 introduces an important layer of functional antagonism within the TCP family, suggesting that balanced TCP activity, rather than simple activation, is required for proper developmental control.

Developing climate-resilient crops

Seed priming is a widely adopted seed technology of growing importance in the context of climate change, as it enhances germination and early seed growth through controlled pre-sowing hydration that activates metabolism without radicle emergence, leading to improved uniformity, stress tolerance, vigor, yield, and overall crop performance. In their review, Gohari *et al.* (2026) present a comprehensive synthesis of seed priming as a cornerstone strategy for enhancing crop resilience under a changing climate. They examine established approaches (hydropriming, osmopriming, and biopriming) and also focus discussion on nanopriming. The forward-looking perspective on smart nanocarrier systems, including bio-based, biodegradable, and biocompatible platforms capable of delivering diverse bioactive compounds, highlights nanopriming as a promising bridge between fundamental seed biology and climate-resilient crop management. Macovei *et al.* (2026) evaluate the potential of seed priming as a strategy to enhance multi-stress tolerance, emphasizing the DNA damage repair (DDR) machinery as a key component of the molecular regulatory network that safeguards genome integrity in seeds. The authors further propose that targeted modulation of DDR pathways through seed priming may represent an innovative approach for the seed sector, supporting the development of more resource-efficient, resilient, and sustainable agricultural systems.

Nanotechnologies are emerging as a new extension of priming approaches by offering innovative tools to modulate seed physiology with enhanced precision and durability. Nanomaterials offer new opportunities in crop production, including improved seed performance, agrochemical delivery, and plant monitoring. Seeds are increasingly recognized as both targets and tools in nanotechnology. Bodor *et al.* (2026) provide a timely perspective by linking nanomaterials to seed priming and challenging the assumption that their effects require physical entry into seeds. Instead, they show that nanomaterials can modulate seed physiology through surface interactions and signaling alone, expanding current models of seed–nanomaterial interactions. Importantly, they also highlight seeds as sustainable platforms for nanomaterial synthesis, aligning seed nanotechnology with circular and environmentally responsible farming practices.

Beside improvement in seed technologies, integrated and high-resolution omics can also be considered as a foundational toolkit for breeding climate-resilient crops and optimizing seed-based agricultural practices. In their review, Auroux *et al.* (2026) underscore the central role of omics technologies in safeguarding global food security under changing environmental conditions. In an integrated perspective, they show how the convergence of epigenomics, genomics, transcriptomics, proteomics, and metabolomics has enabled reconstruction of the complex regulatory networks governing seed life cycles in both Arabidopsis and crop species. Interestingly, they underline that single-cell and spatial omics approaches represent a conceptual leap for the field by revealing previously hidden cell types, tissue-specific programs, and spatially resolved regulatory mechanisms within seeds. By linking these molecular insights to crop domestication, trait control, and seed vigor, this work moves beyond descriptive biology toward practical relevance.

Beyond the embryo: how seed tissues coordinate germination

Seeds characterized by underdeveloped embryos embedded within abundant endosperm tissue, referred to as morphological dormancy (MD), are considered to represent the ancestral state in the evolution of seed dormancy (Willis *et al.*, 2014). Despite their evolutionary significance, the molecular regulation of dormancy and germination in MD seeds remains poorly understood. Using celery (*Apium graveolens*) as a model species, Walker *et al.* (2026) demonstrated that elevated temperatures inhibit germination by suppressing the initiation of embryo growth through a GA–ABA-dependent regulatory mechanism. In contrast, under chilling and low-temperature conditions, embryo growth and the expression of GA-responsive genes involved in endosperm degradation and embryo growth were delayed in a manner consistent with the duration of thermal treatment. Together, these findings indicate that the thermal–hormonal regulation of germination in MD seeds fundamentally differs from that operating in seeds with fully developed embryos.

Pennycress (*Thlaspi arvense*) is an emerging oilseed crop and a valuable model for seed genetics; however, its seeds frequently exhibit dormancy that requires time-consuming and costly treatments to overcome, making reduced dormancy a key target for domestication. Ding *et al.* (2026) investigated the anatomical and chemical properties of the seed coat, together with associated seed traits, in a *TRANSPARENT TESTA 8* (*tt8*) mutant generated by CRISPR (clustered regularly interspaced palindromic repeats)-based genome editing. Histochemical analyses combined with complementary analytical techniques revealed reduced levels of aromatic compounds and cell wall polysaccharides in the mutant seed coat, accompanied by increased seed coat permeability. In addition, *tt8* seeds displayed enlarged embryos without detectable anatomical defects in either the embryo or the endosperm. The authors propose that enhanced imbibition resulting from increased seed coat permeability may facilitate more rapid germination, while simultaneously predisposing the seeds to accelerated aging. Collectively, these findings advance our understanding of the molecular regulation of seed coat-associated traits in pennycress and provide insights relevant to its domestication.

Lastly, Figueiredo and Sharm (2026) address a central but often underappreciated dimension of seed biology: the dynamic and coordinated dialogue among the embryo, endosperm, and seed coat. While these interactions are classically discussed in the context of seed development and final seed traits, their relevance extends well beyond embryogenesis and directly informs our understanding of seed dormancy and germination mechanisms. By emphasizing tissue–tissue communication, this review bridges developmental seed biology with functional germination biology. Variability in signaling pathways across embryo, endosperm, and seed coat helps to explain natural variation in dormancy and germination. In a wider agronomic context, this framework is particularly relevant for improving seed performance under climate change, suggesting that advancing seed innovation and breeding strategies requires moving beyond compartmentalized views of seed tissues.

Conclusion and future perspectives

Together, the contributions in this Special Issue illustrate how germination results from the dynamic integration of environmental cues, molecular networks, and coordinated interactions among embryo, endosperm, and seed coat. They also demonstrate that seed traits relevant for climate resilience are shaped not only at germination but throughout seed development, opening up new opportunities for intervention upstream of sowing. Advances in seed priming, nanotechnologies, and high-resolution omics provide powerful and complementary tools to translate fundamental insights into practical strategies for agriculture. Looking ahead, combining tissue-resolved biology with innovative seed technologies and breeding approaches will be essential to develop robust, climate-ready seeds capable of sustaining food production under increasingly unpredictable environments.

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Keywords: Dormancy, germination, seed, seed technologies and omics, seed tissues, vigor.

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