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ETHYLENE IN SEED PHYSIOLOGICAL QUALITY: A REVIEW

ETILENO NA QUALIDADE FISIOLÓGICA DE SEMENTES: REVISÃO DE LITERATURA

ETILENO EN LA CALIDAD FISIOLÓGICA DE SEMILLAS: REVISIÓN DE LA LITERATURA

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ABSTRACT

Ethylene plays a central role in the regulation of seed dormancy, germination, and vigor, acting as a strategic modulator of the interaction between hormonal pathways and redox signaling. This review aimed to integrate recent evidence on ethylene biosynthesis and signaling, its interaction with abscisic acid (ABA), gibberellins (GAs), and reactive oxygen species (ROS), and its implications for seed physiological quality. The analyzed literature demonstrates that ethylene influences the transition from quiescence to active growth by modulating hormonal sensitivity, promoting metabolic activation during imbibition, and facilitating the controlled weakening of covering tissues. Functional antagonism with ABA and cooperation with GAs constitute a regulatory axis that is crucial for dormancy release, while integration with the redox state contributes to the fine-tuning of germination under variable environmental conditions. Evidence also indicates that ethylene responsiveness may affect vigor-related parameters, including germination speed and uniformity, as well as tolerance to abiotic stresses. Nevertheless, important gaps remain regarding interspecific variability in ethylene sensitivity, the dynamics of ACC homeostasis during storage, and the role of this hormone in seeds subjected to aging. Overall, ethylene should be understood as a component of an adaptive regulatory network integrating hormonal, metabolic, and environmental signals, representing a promising target for advances in seed science and technology.

Keywords: Ethylene; Seed germination; Seed dormancy; Seed vigor; Abscisic acid; Reactive oxygen species.

RESUMO

O etileno desempenha papel central na regulação da dormência, germinação e vigor de sementes, atuando como modulador estratégico da interação entre vias hormonais e sinais redox. Esta revisão teve como objetivo integrar evidências recentes sobre a biossíntese e sinalização do etileno, com ácido abscísico (ABA), giberelinas (GAs) e espécies reativas de oxigênio (ROS), e suas implicações na qualidade fisiológica de sementes. A literatura analisada demonstra que o etileno influencia a transição da quiescência para o crescimento ativo por meio da modulação da sensibilidade hormonal, da ativação metabólica durante a embebição e do enfraquecimento controlado dos tecidos de cobertura. O antagonismo funcional com ABA e a cooperação com GAs configuram um eixo regulatório determinante para a superação da dormência, enquanto a integração com o estado redox contribui para o ajuste fino da germinação sob condições ambientais variáveis. Evidências também indicam que a responsividade ao etileno pode influenciar parâmetros associados ao vigor, como velocidade e uniformidade de germinação, além da

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tolerância a estresses abióticos. Contudo, persistem lacunas quanto à variabilidade interespécies na sensibilidade ao etileno, à dinâmica da homeostase de ACC durante o armazenamento e ao papel desse hormônio em sementes submetidas ao envelhecimento. Conclui-se que o etileno deve ser compreendido como componente de uma rede regulatória adaptativa que integra sinais hormonais, metabólicos e ambientais, representando alvo promissor para avanços na ciência e tecnologia de sementes.

Palavras-chave:
Etileno; Germinação de sementes; Dormência; Vigor de sementes; Ácido abscísico; Espécies reativas de oxigênio.

RESUMEN

El etileno desempeña un papel central en la regulación de la dormancia, la germinación y el vigor de las semillas, actuando como modulador estratégico de la interacción entre vías hormonales y señales redox. Esta revisión tuvo como objetivo integrar evidencias recientes sobre la biosíntesis y señalización del etileno, su interacción con el ácido abscísico (ABA), las giberelinas (GAs) y las especies reactivas de oxígeno (ROS), así como sus implicaciones en la calidad fisiológica de las semillas. La literatura analizada demuestra que el etileno influye en la transición desde la quiescencia hacia el crecimiento activo mediante la modulación de la sensibilidad hormonal, la activación metabólica durante la imbibición y el debilitamiento controlado de los tejidos de cobertura. El antagonismo funcional con el ABA y la cooperación con las GAs configuran un eje regulatorio determinante para la superación de la dormancia, mientras que la integración con el estado redox contribuye al ajuste fino de la germinación bajo condiciones ambientales variables. Asimismo, la evidencia indica que la respuesta al etileno puede influir en parámetros asociados al vigor, como la velocidad y uniformidad de la germinación, además de la tolerancia a estreses abióticos. No obstante, persisten vacíos de conocimiento respecto a la variabilidad interespecífica en la sensibilidad al etileno, la dinámica de la homeostasis del ACC durante el almacenamiento y el papel de esta hormona en semillas sometidas a envejecimiento. Se concluye que el etileno debe entenderse como un componente de una red regulatoria adaptativa que integra señales hormonales, metabólicas y ambientales, representando un objetivo prometedor para avances en la ciencia y tecnología de semillas.

Palabras clave: Etileno; Germinación de semillas; Dormancia; Vigor de semillas; Ácido abscísico; Especies reactivas de oxígeno.

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1 - Introduction

Seed physiological quality constitutes one of the fundamental pillars of modern agricultural production, being decisive for crop establishment, emergence uniformity, stand formation, and yield potential. This concept encompasses attributes such as viability, vigor, storage capacity, and performance under adverse conditions, reflecting the interaction among genetic, environmental, and technological factors throughout the production cycle (Carvalho; Nakagawa, 2000; Marcos Filho, 2015). From a physiological perspective, germination represents the transition from a metabolically quiescent state to intense biochemical and structural activity, involving membrane reorganization, protein synthesis, reserve mobilization, and activation of regulatory hormonal pathways (Bewley; Black, 1994; Bewley et al., 2013).

Among the plant regulators involved in this process, ethylene (C_2H_4) stands out as a multifunctional gaseous phytohormone, participating in the regulation of germination, dormancy release, and responses to abiotic stresses (Matilla, 2000; Lin et al., 2009). During imbibition, ethylene biosynthesis is enhanced through the precursor 1-aminocyclopropane-1-carboxylic acid (ACC), catalyzed by the enzymes ACC synthase (ACS) and ACC oxidase (ACO), integrating environmental and hormonal signals that modulate germination progression (Kępczyński, 1997).

Classical and contemporary studies demonstrate that ethylene promotes embryo growth and reduces mechanical constraints imposed by the seed coat and endosperm, while also acting antagonistically to abscisic acid (ABA), a hormone traditionally associated with dormancy maintenance (Kucera; Cohn; Leubner-Metzger, 2005; Corbineau, 2014). This hormonal interaction is critical for the balance between dormancy and germination, particularly under limiting environmental conditions such as extreme temperatures, water restriction, or hypoxia.

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Beyond germination itself, evidence indicates that ethylene influences key components of seed vigor, including germination speed, emergence uniformity, stress tolerance, and metabolic recovery capacity (Nascimento, 2003; Corbineau, 2014). Its participation in hormonal interactions with gibberellins and reactive oxygen species (ROS) establishes a complex regulatory network linking environmental cues to gene expression and physiological performance.

In this context, understanding the role of ethylene in seed physiological quality is essential from both a fundamental perspectiveencompassing molecular and biochemical mechanismsand an applied standpoint, considering implications for seed technology, post-harvest management, and stress mitigation. Therefore, this review aims to integrate major scientific advances regarding ethylene biosynthesis, signaling, and hormonal interactions, discussing their implications for germination, dormancy, and seed vigor across different plant species.

2- Methodology

This review was conducted using a structured narrative approach, adopting systematized criteria for literature search, selection, and analysis concerning the role of ethylene in seed physiological quality. Unlike a systematic review, which follows rigid protocols such as PRISMA and often includes exhaustive search strategies and quantitative meta-analysis, a structured narrative review allows broader conceptual integration of the literature while maintaining transparent and organized criteria for article selection and interpretation. This approach is appropriate for synthesizing physiological, biochemical, and molecular evidence related to ethylene signaling in seeds.

Bibliographic research was performed using the Web of Science, Scopus, PubMed, and ScienceDirect databases, selected due to their coverage of high-impact journals in Plant Physiology, Molecular Biology, and Seed

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Technology. Search terms in English were combined using Boolean operators, including "ethylene AND seed germination," "ethylene AND seed dormancy," "ethylene AND seed vigor," "ethylene signaling AND seeds," "ACC AND seed physiology," and "ROS AND seed germination AND ethylene." Publications from 2000 to 2025 were considered, with particular emphasis on studies published within the last decade.

The initial database search returned approximately 145 records. After removing duplicate entries identified across databases, 112 unique articles remained. A preliminary screening based on titles and abstracts excluded studies not directly related to ethylene-mediated regulation of seed physiology, reducing the dataset to 46 articles. These publications were subsequently evaluated through full-text analysis according to the defined inclusion and exclusion criteria. From this process, 24 studies were selected as the core literature supporting the present review.

Peer-reviewed original articles and scientific reviews were included, encompassing both model species such as *Arabidopsis thaliana* and economically relevant crop species. Priority was given to studies addressing ethylene biosynthesis and signaling mechanisms, hormonal interactions with abscisic acid and gibberellins, integration with reactive oxygen species, and implications for vigor, dormancy, abiotic stress responses, and seed physiological performance. Non-peer-reviewed works, conference abstracts without full publication, studies focused exclusively on vegetative tissues or fruits, and articles without full-text access were excluded.

Initial screening was conducted through title and abstract evaluation to determine thematic relevance. Selected articles were subsequently analyzed in full, considering methodological quality, experimental robustness, and conceptual contribution. Although systematic reviews emphasize strict reproducibility and quantitative synthesis, the present structured narrative review prioritizes critical interpretation and conceptual integration of the literature.

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Final selection prioritized studies published in Q1 journals within the fields of Agricultural Sciences, Plant Physiology, and Molecular Biology. The final set of 24 selected publications included classical references in seed physiology and recent studies addressing molecular signaling, hormonal interactions, and redox regulation of seed germination. The selected literature was organized into thematic axes addressing ethylene biosynthesis and signaling, dormancy, hormonal interactions, redox integration, vigor, and technological applications. The analysis was conducted in an integrative and critical manner, aiming to identify convergences, scientific gaps, and practical implications for seed technology, establishing connections between molecular, hormonal, and measurable physiological responses.

3- Literature Review

3 . 1 Ethylene Biosynthesis and Signaling in the Physiological Regulation of Seeds

The regulation of seed germination and physiological quality involves a complex hormonal network in which ethylene (C_2H_4) plays a central role through its interaction with dormancy pathways, reserve mobilization, and stress responses. Ethylene biosynthesis occurs via the Yang cycle pathway, in which the precursor 1-aminocyclopropane-1-carboxylic acid (ACC) is produced from S-adenosyl-L-methionine (SAM) by the action of ACC synthase (ACS), followed by its conversion into ethylene by ACC oxidase (ACO). The regulation of ACS and ACO is highly responsive to environmental and physiological stimuli, conferring a dynamic nature to ethylene production that adjusts to metabolic shifts during imbibition and early germination (Corbineau et al., 2024).

Ethylene signaling involves a membrane receptor system that, in the absence of the hormone, maintains the kinase CTR1 in an active state, thereby repressing downstream signaling events. Ethylene binding inactivates CTR1, allowing activation of EIN2 and subsequent stabilization and activation of transcription factors such as EIN3 and EIL1. These factors regulate

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transcriptional programs associated with cell expansion, reserve mobilization, and dormancy release, integrating hormonal signaling with the physiological status of the seed (Corbineau et al., 2024; Shukla et al., 2025).

Recent reviews reinforce that seed responsiveness to ethylene depends on dormancy status and species, with positive effects on germination reported in several crops. Ethylene facilitates endosperm weakening and radicle protrusion through interactions with other hormones, particularly abscisic acid (ABA) and gibberellins (GAs), and by interacting with reactive oxygen species (ROS) during the early phases of imbibition. This hormonal interaction is critical for shifting the balance from an inhibitory to a metabolically active state that characterizes germination (Shukla et al., 2025).

Contemporary empirical evidence supports specific physiological mechanisms. In peanut (*Arachis hypogaea*), recent studies demonstrate that ethylene application enhances GA biosynthesis, particularly GA_3 and GA_4, increases the expression of genes associated with cell wall modification such as expansins and pectinesterases, and reduces the expression of germination inhibitors such as *ABI5*, thereby promoting fatty acid reserve mobilization and accelerating seedling emergence. These responses reflect coordinated hormonal regulation that attenuates ABA inhibition and enhances embryonic axis growth, integrating physiological and molecular dimensions (Cui et al., 2025).

Furthermore, modulation of ACC homeostasis, including precursor conjugation and transport, has emerged as a critical aspect of pathway regulation. Increasing evidence that ACC may act independently of ethylene suggests additional signaling mechanisms during the transition from quiescence to germination, particularly under abiotic stress conditions. This reinforces the need for careful interpretation when ACC is used as an exogenous substitute for ethylene in experimental systems (Pattyn; Vaughan-Hirsch; Van de Poel, 2021; Mou et al., 2020).

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The integration of biosynthetic and signaling components with measurable physiological responses—such as germination speed and uniformity, dormancy sensitivity, and reserve mobilization—positions ethylene as a central regulator of seed physiological quality. However, important gaps remain, including the epigenetic modulation of ethylene responses and interspecific differences in hormonal sensitivity, representing key frontiers for future research.

3.2 Hormonal Interaction and Redox Integration Between Ethylene, ABA, Gibberellins, and Reactive Oxygen Species

The regulation of seed dormancy and germination results from an integrated network of hormonal and redox signals, in which ethylene functions as a strategic modulator of the balance among abscisic acid (ABA), gibberellins (GAs), and reactive oxygen species (ROS). The ABA–GA axis is traditionally recognized as the central regulatory core of the dormancy–germination transition, with the ABA/GA ratio frequently used as a physiological indicator of seed status (Kucera; Cohn; Leubner-Metzger, 2005). In this framework, ethylene does not act independently but directly influences tissue sensitivity and the dynamics of this hormonal balance (Corbineau, 2014; Corbineau et al., 2024).

ABA is the primary hormone associated with dormancy induction and maintenance, promoting repression of embryonic growth and metabolic stability under adverse conditions. Genetic evidence shows that ethylene-insensitive mutants exhibit increased ABA sensitivity and deeper dormancy, indicating that the ethylene pathway plays an antagonistic role in ABA signaling (Corbineau, 2014). This antagonism may occur through reductions in ABA content or through modulation of genes involved in ABA signaling and catabolism, thereby altering embryonic responsiveness during imbibition.

Conversely, gibberellins promote embryonic growth processes, including cell elongation and weakening of covering tissues. The literature

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indicates that ethylene can potentiate GA action either by stimulating GA biosynthesis or by enhancing tissue sensitivity to GA signaling, contributing to a functional reduction in the ABA/GA ratio and favoring radicle protrusion (Kucera; Cohn; Leubner-Metzger, 2005; Corbineau et al., 2024). This hormonal cooperation reinforces the concept that ethylene facilitates the physiological transition from dormancy to active growth.

Nevertheless, recent studies indicate that the role of ethylene may vary depending on species, genotype, and environmental conditions. Under salt stress, for instance, interactions between ethylene and ABA may produce differential responses in which ethylene can either attenuate or intensify ABA signaling depending on stress intensity and physiological context (Alonso et al., 2024). Such variability underscores that hormonal interactions must be interpreted as dynamic and environment-dependent systems.

Beyond classical hormonal interactions, ROS have emerged as essential components of this regulatory network. During imbibition, controlled ROS production acts as a necessary signal for germination, contributing to mechanical weakening of barriers, metabolic activation, and modulation of hormonal pathways (Bailly, 2019). ROS may influence both ABA catabolism and activation of growth-promoting pathways, integrating with ethylene and GA signaling (El-Maarouf-Bouteau; Bailly, 2008; Farooq et al., 2021).

Recent reviews indicate that this integration also involves calcium signaling networks, nitric oxide, and MAPK cascades, as well as potential epigenetic mechanisms that fine-tune gene expression during the transition from quiescence to germination (Wang et al., 2024; Bykova et al., 2025). Thus, redox status should not be interpreted merely as a metabolic consequence but as an active regulatory element that interacts with hormonal pathways and determines germination speed and uniformity.

From the perspective of seed physiological quality, this integrated network suggests that vigor and stress performance depend less on absolute

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levels of a single hormone and more on the stability and responsiveness of the hormonal-redox system as a whole. In this scenario, ethylene acts as a modulator of ABA sensitivity, GA effectiveness, and the permissive redox window for germination, potentially assuming either a promotive or restrictive role depending on the physiological context of the seed.

It is important to highlight that the physiological role of ethylene during germination is not uniform across plant species or seed categories. Seeds with different dormancy mechanisms or storage behaviors may exhibit distinct sensitivities to ethylene signaling. For example, in orthodox seeds such as many cereals and legumes, ethylene frequently promotes dormancy release and germination by interacting with the ABA–GA balance. In contrast, species with deeper physiological dormancy or complex seed coat barriers may display a more limited response to ethylene alone, requiring the combined action of additional hormonal or environmental cues (Matilla, 2000; Corbineau, 2014).

Comparative studies also indicate that model species such as *Arabidopsis thaliana* often show strong transcriptional responses to ethylene signaling, whereas crop species may exhibit more variable physiological responses depending on genotype and environmental conditions. These interspecific differences highlight the importance of interpreting ethylene responses within the ecological and physiological context of each species, avoiding generalized extrapolations across seed types.

3.3 Ethylene, Seed Vigor, and Physiological Quality

Seed physiological quality is defined by the integration of viability, vigor, and performance capacity under adverse conditions, with vigor being particularly associated with the speed, uniformity, and robustness of germination and seedling emergence (Marcos Filho, 2015; Bewley et al., 2013). Although traditionally investigated in the context of dormancy, ethylene also plays a relevant role in determining vigor, especially by modulating the

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efficiency of the metabolic transition occurring during imbibition and through its interaction with cellular repair mechanisms and redox signaling pathways.

During the early phase of imbibition, high-vigor seeds exhibit rapid membrane reorganization, reduced electrolyte leakage, and greater efficiency in mitochondrial respiratory reactivation. Proteomic and physiological studies demonstrate that the early activation of metabolic pathways is associated with the maintenance of cellular integrity and control of oxidative stress (Rajjou et al., 2012). In this context, ethylene may function as a modulator of metabolic activation, influencing both the expression of genes related to reserve mobilization and the antioxidant response during the initial hours of hydration.

The literature indicates that ethylene is involved in the controlled weakening of covering tissues and in facilitating embryonic axis growth, processes that directly impact germination rate, one of the main components of vigor (Matilla, 2000; Corbineau, 2014). Ethylene-mediated regulation of enzymes associated with cell wall modification, such as expansins and endo-β-mannanases, contributes to reducing mechanical barriers to radicle elongation, thereby promoting faster and more uniform germination.

Moreover, vigor is strongly associated with the capacity of seeds to tolerate abiotic stresses during germination. Experimental evidence shows that ethylene signaling can modulate responses to salinity, water deficit, and thermal stress, frequently interacting with ROS and the ABA–GA hormonal network (Farooq et al., 2021; Alonso et al., 2024). This interaction is particularly relevant because high-vigor seeds tend to display greater efficiency in redox regulation, maintaining ROS at signaling levels without reaching oxidative damage thresholds (Bailly, 2019).

Another critical aspect concerns deterioration during storage. Loss of vigor is associated with oxidative damage accumulation, membrane degradation, and alterations in hormonal homeostasis (Marcos Filho, 2015). Although the literature remains limited regarding the direct involvement of

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ethylene in stored seeds, evidence suggests that changes in ethylene sensitivity and ACC biosynthesis may occur in aged seeds, negatively affecting the coordination between embryonic growth and seed coat weakening. This represents an important knowledge gap and a promising frontier for future research.

Transcriptomic studies reveal that high-vigor seeds display distinct expression profiles of genes associated with hormonal signaling, energy metabolism, and antioxidant defense (Dekkers et al., 2013). Considering that ethylene signaling converges on transcription factors such as EIN3 and EIL1, which regulate multiple stress- and growth-responsive genes, it is plausible that differences in ethylene sensitivity contribute to physiological performance variability among seed lots.

Conceptually, ethylene may be interpreted as a modulator of the physiological “permissive window” for efficient germination. In vigorous seeds, its signaling appears to integrate reserve mobilization, redox control, and adjustment of the ABA–GA balance, promoting rapid and synchronized germination. In deteriorated seeds or under severe stress conditions, however, this pathway may become insufficient or dysregulated, compromising uniformity and emergence.

Thus, understanding the role of ethylene in seed physiological quality requires moving beyond its classical function in dormancy and considering its integration with bioenergetic, redox, and structural processes that determine vigor. Future investigations combining hormonal, metabolomic, and transcriptomic analyses may provide more precise insights into how ethylene sensitivity contributes to physiological variability among seed lots and species, expanding its potential applications in seed technology.

An additional aspect that deserves attention concerns seed aging during storage, which represents one of the main factors responsible for the decline in physiological quality. Seed deterioration is a progressive and

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irreversible process associated with membrane disorganization, accumulation of oxidative damage, and reduced metabolic efficiency. During aging, lipid peroxidation and protein oxidation lead to increased electrolyte leakage and impaired mitochondrial activity, ultimately reducing germination speed and uniformity (Bewley et al., 2013; Marcos Filho, 2015).

In this context, alterations in hormonal sensitivity may occur, including changes in ethylene biosynthesis and signaling pathways. Some studies suggest that aged seeds may exhibit reduced responsiveness to ethylene or altered ACC metabolism, which can compromise the coordination between embryo growth and the weakening of surrounding tissues. Additionally, oxidative stress associated with seed deterioration may interfere with the redox signaling network that interacts with ethylene and other hormones during germination (Rajjou et al., 2012; Bailly, 2019).

Although direct experimental evidence remains limited, the interaction between aging processes and ethylene signaling represents an important research frontier. Understanding how storage conditions influence ethylene responsiveness may contribute to improving seed longevity management and the prediction of seed lot performance after prolonged storage.

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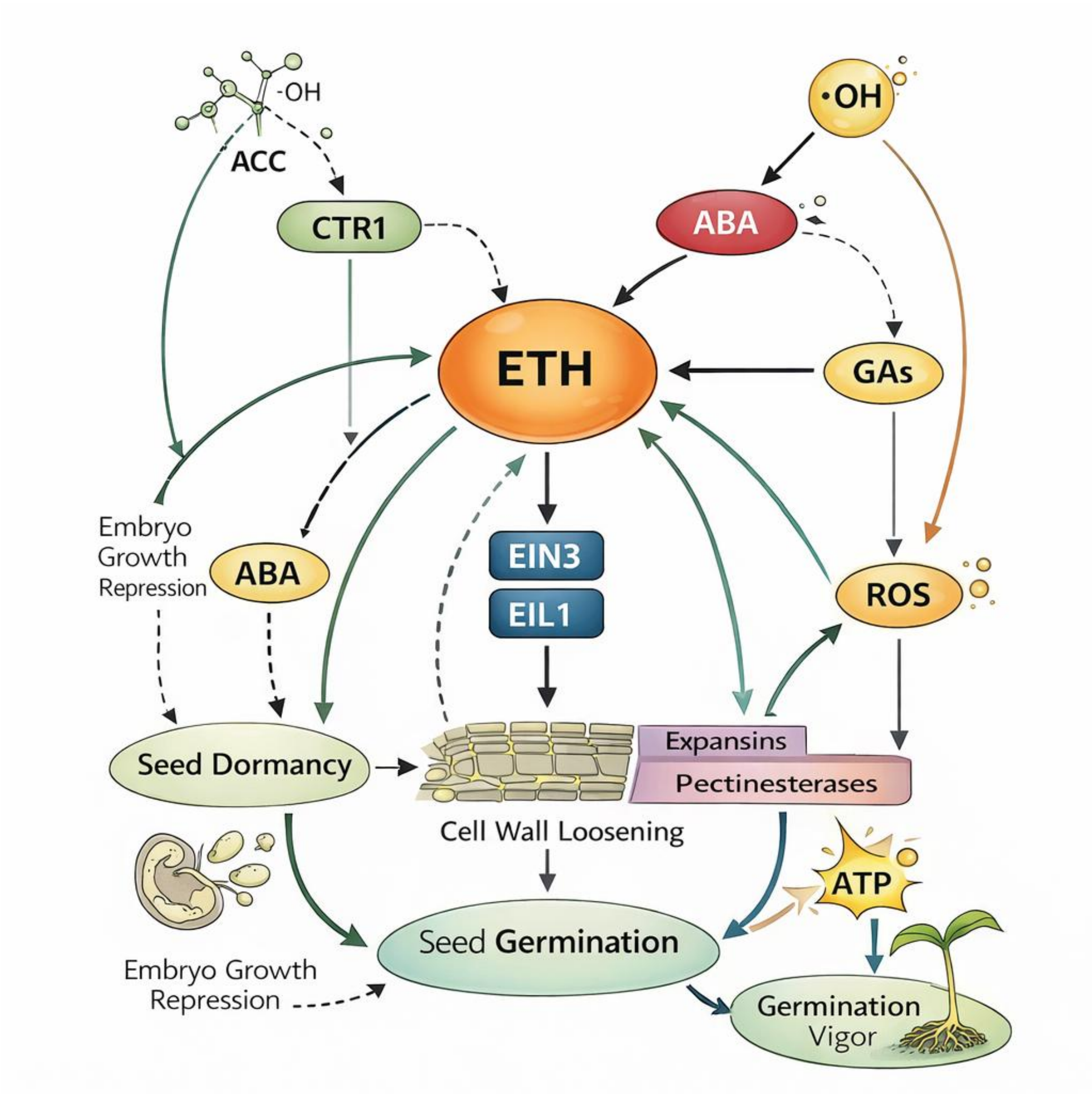

Source: Prepared by the authors with the assistance of artificial intelligence.

Figure 1. Integrative conceptual model of the hormonal–redox network regulating seed dormancy, germination, and vigor.

Ethylene (ETH) acts as a central regulator of seed physiological processes by integrating hormonal signaling and redox status. ETH biosynthesis originates from the precursor 1-aminocyclopropane-1-carboxylic acid (ACC) and activates downstream signaling components such as EIN3 and EIL1. Through these pathways, ethylene interacts antagonistically with abscisic acid (ABA), which maintains seed dormancy by repressing embryo growth, and

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synergistically with gibberellins (GAs), which promote embryo elongation and radicle protrusion. Reactive oxygen species (ROS) function as signaling molecules during imbibition, contributing to cell wall weakening, reserve mobilization, and metabolic activation. ETH also stimulates the expression of cell wall–modifying enzymes, including expansins and pectinesterases, facilitating endosperm weakening and radicle emergence. The integration of hormonal and redox signals ultimately regulates ATP production, seed germination, and seedling vigor. The model highlights the dynamic balance between dormancy maintenance and germination promotion, emphasizing ethylene as a key modulator of seed physiological quality.

3.4 Applications in Seed Technology and Future Perspectives

Advances in understanding ethylene biosynthesis, signaling, and hormonal integration open concrete possibilities for applications in seed technology. Traditionally, the management of physiological quality has focused on practices such as maturation control, drying, processing, and storage. However, growing knowledge of ethylene's role in modulating dormancy, vigor, and stress responses allows for more targeted approaches based on hormonal and redox regulation.

Among potential strategies, pre-germinative treatments such as priming stand out, as they promote controlled metabolic activation without allowing radicle protrusion. Evidence indicates that priming can alter hormonal balance and modulate pathways associated with ethylene, resulting in increased germination speed and uniformity (Paparella et al., 2015; Paul; Dey; Kundu, 2022). These effects are often associated with membrane reorganization, activation of antioxidant systems, and enhanced efficiency of cellular repair mechanisms, processes in which ethylene may act as a regulatory component of metabolic transition.

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Another promising field involves the use of ethylene pathway modulators, such as 1-methylcyclopropene (1-MCP), which blocks ethylene receptors, or biosynthesis inhibitors such as aminoethoxyvinylglycine (AVG). Although widely used in fruit post-harvest management, their application in seeds remains incipient and lacks standardized protocols. Studies indicate that manipulating ethylene sensitivity can alter dormancy depth and germination rates, but the effects depend on species, physiological status, and environmental conditions (Corbineau, 2014). Therefore, technological extrapolation requires caution and crop-specific validation.

In the context of abiotic stresses, particularly water deficit and salinity, modulation of ethylene signaling has been associated with improved tolerance during germination, often via interaction with ROS and ABA (Farooq et al., 2021; Alonso et al., 2024). This evidence suggests that selecting or inducing enhanced ethylene responsiveness may represent an indirect strategy to increase seed lot resilience under adverse environmental conditions, particularly relevant in the context of climate change.

Beyond physiological approaches, omics tools offer new perspectives for integrating ethylene as a marker of physiological quality. Transcriptomic and proteomic studies demonstrate that high-vigor seeds exhibit distinct expression patterns of genes related to hormonal signaling and energy metabolism (Dekkers et al., 2013; Rajjou et al., 2012). The identification of molecular signatures associated with ethylene sensitivity may contribute to the development of predictive performance indicators, supporting breeding programs and seed certification systems.

Despite these advances, significant gaps remain. Understanding how ACC homeostasis varies during storage and artificial aging is still limited, as is the role of ethylene in recalcitrant seeds. Comparative studies among species regarding genetic variability in ethylene sensitivity and its relationship with vigor are also scarce. Another challenge lies in disentangling direct ethylene effects

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from those mediated by interactions with ABA, GAs, and redox status, requiring integrated experimentais approaches and refined physiological models.

Conceptually, ethylene should be interpreted not merely as a dormancy regulator but as a component of an adaptive network that adjusts seeds to environmental conditions at the onset of germination. Translating this knowledge into seed technology will depend on integrating classical physiology, molecular biology, and agronomic practices, enabling more precise and sustainable interventions.

In summary, understanding ethylene dynamics in seed physiological quality broadens the strategic framework for optimizing germination and seedling emergence, particularly under stress conditions. Consolidating this field will require multidisciplinary investigations connecting molecular, hormonal, and bioenergetic levels to actual agronomic performance.

It is important to distinguish between mechanisms that are well established in the literature and those that remain hypothetical or emerging. Strong experimental evidence supports the role of ethylene in dormancy release, endosperm weakening, and interactions with ABA and gibberellins during germination. These processes have been consistently demonstrated across multiple species and experimental systems, forming the core conceptual framework for understanding ethylene action in seeds.

Conversely, several aspects discussed in recent studies should still be interpreted as prospective hypotheses rather than consolidated evidence. These include the role of ACC as an independent signaling molecule, the epigenetic modulation of ethylene responses during germination, and the potential use of ethylene sensitivity as a biomarker of seed vigor. Although promising, these hypotheses require further validation through integrated physiological, molecular, and omics-based approaches.

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Future investigations combining transcriptomic, metabolomic, and physiological analyses will be essential to clarify these mechanisms and determine their practical relevance for seed technology and crop improvement.

4- Final Considerations

In light of contemporary evidence, ethylene emerges as a central component of the regulatory network governing seed dormancy, germination, and vigor. Its role extends beyond the classical function of dormancy release, positioning ethylene as a strategic modulator integrating hormonal balance, redox status, and metabolic reprogramming during imbibition. The dynamic interaction among ethylene, abscisic acid, gibberellins, and reactive oxygen species establishes a regulatory system responsive to environmental conditions, capable of adjusting the transition from quiescence to active growth.

From the perspective of seed physiological quality, ethylene contributes to the coordination of essential processes, including reserve mobilization, weakening of covering tissues, antioxidant activation, and respiratory reactivation. The efficiency of this integration is closely associated with germination speed and uniformity, which are core parameters of vigor. However, the effects of ethylene are not universal and depend on the physiological status of the seed, genotype, and environmental conditions, potentially assuming either promotive or restrictive roles depending on stress intensity and hormonal sensitivity.

Despite significant advances in characterizing ethylene biosynthesis and signaling pathways, important knowledge gaps remain, particularly regarding interspecific variability in hormonal responsiveness, the dynamics of ACC homeostasis during storage, and the role of ethylene in seeds subjected to natural or artificial aging. Furthermore, understanding of the epigenetic and redox mechanisms that modulate the integration between ethylene and other hormonal regulators in the context of vigor remains limited.

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Consolidating knowledge in this field will require multidisciplinary approaches integrating classical seed physiology, molecular biology, omics-based analyses, and agronomic performance evaluation. Progress in this direction may enable the development of more precise hormonal modulation strategies, selection of genotypes with enhanced physiological stability, and refinement of seed conditioning techniques, thereby contributing to more resilient agricultural systems under increasingly challenging climatic scenarios.

In summary, elucidating the role of ethylene in seed physiological quality not only advances fundamental understanding of germination mechanisms but also establishes conceptual and technological foundations for innovation in seed science and technology.

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