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UNVEILING AUXIN'S ROLE IN SEED DORMANCY, GERMINATION AND POSSIBLE IMPACT OF IAA PRODUCING PGPR IN SEED BIO-PRIMING AND PLANT GROWTH

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Abstract

Seed dormancy and germination are key stages in the growth and development of plants and are pivotal to the survival and propagation of plants. Both dormancy and germination are very complex biological processes that are controlled by a wide range of important genes, hormone levels, signal transduction, and external environmental conditions. By ensuring coordination with favorable conditions, dormancy assists in avoiding premature germination during unfavorable conditions. Innate and enforced dormancy are the two main reasons for dormancy. Dormancy mechanisms are controlled by external factors, and germination can only begin under certain circumstances. With the resumption of metabolic functions and the use of stored energy, germination signals change from dormant to active growth. For the management of ecosystems, agriculture, and conservation, it is essential to understand seed dormancy and germination. Various studies reported that abscisic acid (ABA) is a positive regulator of dormancy induction and gibberellins (GA) counteract ABA effects and release dormancy. Similarly, some of recent studies revealed that indole-3-acetic acid (IAA) has a positive regulatory effect on seed dormancy and controls seed dormancy through stimulation of ABA. However, some of the researchers reported that IAA-priming and IAA-producing PGPRs enhance the germination and growth of the plants. Researchers also revealed that bio-priming based on rhizobacteria that produce IAA increases the germination of seeds and early growth. Examining the relationships among auxin (IAA), IAA-producing PGPRs, and seed biology reveals contradictory opinions for agricultural uses. Understanding this dynamic enhances our knowledge of basic mechanisms involved in seed bio-priming with IAA-producing PGPR. In the present article, we aimed to report the roles of IAA in seed dormancy and germination. We also discussed the conflicting findings on the role that IAA plays in seed dormancy, the crosstalk of IAA and ABA, and the possible role of IAA-producing rhizobacteria in seed bio-priming and plant growth.

Keywords: ABA; IAA; Bio-priming; IAA-producing PGPR; Plant growth; Plant-microbe interactions; Seed dormancy and germination.

Introduction

Plant life cycles include two key stages (seed dormancy and germination) that are essential for both their survival and propagation (Klupczyńska & Pawłowski, 2021, Penfield, 2017, Sajeev *et al*., 2024). A seed's temporary halt to growth and development is known as seed dormancy, and the restart of growth that results in the development of a new plant is known as germination (Penfield, 2017, Longo *et al*., 2020). Dormancy allows seeds to endure adverse environmental conditions and postpone germination until they are exposed to favorable conditions (Kildisheva *et al*., 2020, Longo *et al*., 2020). Thus, the question is: What influences a seed's germination decision? Numerous extrinsic environmental cues in addition to the endogenous dormancy of seeds level regulate the complex biochemical and physiological mechanisms involved in germination (Shu *et al*., 2015, Finkelstein *et al*., 2008). With the help of these precisely calibrated modifications, plants may successfully reproduce and disperse by timing their growth to coincide with ideal environmental conditions.

To wait for ideal conditions for seedling development, seeds might postpone germination through dormancy (Sajeev *et al*., 2024). By preventing germination in adverse conditions like drought, heat, or extreme cold, this temporal dispersal approach may increase the survival probability of the seedlings. Moreover, dormant seeds can withstand competition from established vegetation for a long time by remaining intact in the soil seed bank (Cuena Lombraña *et al*., 2024). Thompson *et al*., (2003) revealed that there is confusion in the ecological literature between seed dormancy and persistence in the soil. While some ecologists seem to believe that persistence cannot occur without dormancy, others seem to suggest that the two are nearly identical. They reported that there is no close relationship between dormancy and persistence because dormancy is a characteristic of the seed, not of the environment, the degree of which defines the conditions required to make the seed germinate. The confusion appears to arise from the concept of 'enforced dormancy', which is not genuinely dormancy at all, and would be eliminated if ecologists adopted the definition of dormancy employed by physiologists. However, in a recent study Holloway *et al*., (2021) reported direct evidence for coleorhiza-enforced seed dormancy as a novel mechanism to control germination in grasses.

Broadly, two main categories differentiate why a seed won't sprout, even if it seems like it should: innate dormancy and enforced dormancy. Innate dormancy, also called internal or inherent dormancy, is an internal characteristic of the seed itself. Even in perfect growing conditions (moisture, warmth, sunlight), the seed won't germinate because of its biological makeup. This dormancy mechanism can be broken down by weathering or scarification (scratching the seed coat) i.e. legumes (beans, peas) often have hard seed coats that enforce innate dormancy. On the other hand, enforced dormancy, also known as environmental dormancy, is caused by external factors that prevent germination, even if the seed is internally ready to sprout. Once the unfavorable conditions improve, the seed can then germinate. By understanding the differences between innate and enforced dormancy, gardeners and farmers can tailor their practices to optimize seed germination for various plant species. Dormant seeds seize possibilities for colonization and establishment in new ecosystems by postponing germination until disturbances or gaps in the vegetation arise. Chemical signals, light, moisture, and temperature are some examples of environmental cues that control dormancy mechanisms (Qaderi, 2023). To start germination, seeds require specific environmental conditions, also referred to as germination-promoting or dormant-breaking variables (Carrera-Castaño *et al*., 2020). Because of this synchronization, seedlings have the best chance of surviving by emerging when resources are plentiful and competition is at its lowest. Plants have evolved seed dormancy as an adaptive feature to help them deal with the unpredictability of environmental changes. Dormant seeds enhance the resilience and durability of plants in dynamic ecosystems by acting as a buffer against unfavorable conditions (Longo *et al*., 2020). However, germination signifies the change from a dormant seed to an actively developing seedling, which is an important stage in the growth cycle of plants.

Julius von Sachs (1832–1897), a German botanist, suggested that plants produce “organ-forming substances” that are responsible for the development and growth of various plant organs (Kucera *et al*., 2005). At a very low concentration, the plant hormones gibberellins (GA), ethylene, auxins, cytokinins, and abscisic acid (ABA) have a tremendous effect on plant growth and development. They serve as chemical messengers for higher plants' cells, tissues, and organs to communicate with one another (Baca & Elmerich, 2007, Shah *et al*., 2023). Higher plants have seeds that contain an embryo covered in layers, which serves to ensure the emergence of a new plant. A healthy seed with a temporary failure to germinate is known as a dormant seed. Presently, two main types of physiological seed dormancy have been reported such as coat dormancy and embryo dormancy (Kucera *et al*., 2005). The control of seed dormancy as well as germination is largely dependent on environmental conditions and plant hormones. Auxin (IAA), one of the primary plant hormones, has been well-researched for its capacity to regulate a range of processes, such as cell proliferation, tissue differentiation, tropic development, etc. IAA is thought to be the second hormone type after ABA that leads to seed dormancy (Shuai *et al*., 2016).

Seed germination initiates with the uptake of water through imbibition and is followed by embryo expansion (Bradford, 2017, Louf *et al*., 2018, Raza *et al*., 2023). Such as water uptake by seeds occurs in three distinct stages: stage-I, also known as imbibition, takes place very quickly, while stage-II is a plateau period. A further increase in water absorption doesn't happen until the embryo's axis lengthens and penetrates its covering structures, which occurs at the end of germination (stage-III). During the germination of many different seeds, the rupture of the testa and the endosperm are two distinct and temporally separate events (Kucera *et al*., 2005, Louf *et al*., 2018, Nasreen *et al*., 2015). In *Arabidopsis*, a two-step germination process has been observed, wherein testa rupture occurs first, and then endosperm rupture (Daszkowska-Golec, 2011). IAA is released from the conjugates stored in seed during germination (Ljung *et al*., 2001). The first noticeable swelling of the seeds during imbibition corresponds with a peak of free IAA that occurs before the commencement of root elongation as reviewed by Kucera *et al*., (2005). In another study, Bialek *et al*., (1992) reported that during germination, there is an increase in IAA synthesis in bean seeds. During radicle emergence, free IAA amounts decrease, and the emerging seedling initiates new IAA synthesis. Similarly, the study of Zhao *et al*., (2020) revealed that IAA priming (20 mg L^{-1}) increased the rate of germination of cotton seeds and stimulated the growth of seedlings by controlling the endogenous phytohormones (endogenous ABA content decreased, endogenous IAA and GA contents increased), improved the metabolism of sucrose in germinating seeds, and boost photosynthesis in the seedlings. More recently, Advinda *et al*., (2024) reported that IAA can be produced by fluorescent pseudomonads LAHLS1, LAHT1, LAHCS2, and PfPb3 used in bio-priming, thereby enhancing the growth and germination rate of *C. frutescens* L. seeds. On the other hand, the study of Tabatabaei *et al*., (2016) reported four *Pseudomonas* strains that produce IAA, and the role of exogenous IAA was examined to investigate how they affected the germination of *Triticum turgidum* L. (durum wheat) seeds and the activity of α-amylase. They revealed that every bacterial strain inhibited germination to differing degrees. The suppression of germination and bacterial IAA levels were linked. Depending on the concentration, exogenously applied IAA influenced germination and α-amylase activity, indicating that bacterial IAA may be the source of germination suppression.

It has been frequently suggested that IAA-producing *Pseudomonas* have a dual role in plant development and health, with some bacteria appearing to promote seed germination and others that inhibit it (Tabatabaei *et al*., 2016). While our understanding of IAA's function in seed germination has advanced significantly, there are still several challenges and unresolved questions that hinder us from fully understanding its exact mechanisms. Understanding the temporal and spatial patterns of IAA accumulation and signaling in the seed is a significant challenge. Target genes involved in germination regulation and precisely mapping IAA gradients require the use of genetic tools and advanced imaging techniques due to the complex relationships among IAA production, transport, and signaling pathways. In recent years, there has been a surge in the investigation of germination arrest factors, or GAFs. GAFs are substances produced by microbes that cause an irreversible halt to seed germination (Fang *et al*., 2022). Two GAFs generated by *Pseudomonas* species are 4-formyl aminooxy vinyl glycine (FVG) and L-2-amino-4-methoxy-trans-3-butenoic acid (AMB) (Tabatabaei *et al*., 2016). However, little is known about how GAFs affect seed germination. Investigating the relationships among IAA, IAA-producing PGPRs, and seed germination demonstrated contradictory opinions for different seed types and microbes. In the present article, we aimed to report the roles of IAA in seed dormancy and germination. We also discussed the conflicting findings on the role that IAA plays in seed dormancy and germination, the crosstalk of IAA and ABA, and the possible role of IAA-producing rhizobacteria in seed-specific bio-priming and plant growth and development.

IAA role in seed dormancy: Seed dormancy is a key adaptation mechanism that exists in several plants species, during which seeds pause for the right conditions required for germination (Sajeev *et al*., 2024). According to Soppe & Bentsink (2020) seed dormancy is defined as the absence of germination of a viable seed under conditions that are fit for germination. Seed populations are typically used to measure dormancy, where seed populations exhibiting a certain degree of dormancy might be defined as those that fail to fully sprout under germination-promoting conditions. This phenomenon ensures plant populations' survival, dispersal, and continuity under varied conditions and habitats. In a plant's life cycle, seed dormancy executes some crucial roles, such as temporal dispersal, avoiding competition, timing germination with optimal conditions for growth, and adaptation to complex and unpredictable environmental conditions (Tursun, 2020, Soppe & Bentsink, 2020). We still aren't completely sure how seed dormancy, as well as germination, evolved, even though different dormant mechanisms have been hypothesized as adaptations to distinct habitats inhabited by different plant species. Similarly, it was thought that the major hormones regulating the development of seeds were gibberellin (GAs) and abscisic acid (ABA). However, auxin has now come to light as a crucial component that regulates multiple processes within cells associated with seed development including the induction, modulation, and maintenance of dormancy in combination with ABA (Matilla, 2020).

During the stages of embryogenesis, maturation, and desiccation, seeds experience morphological, physiological, and biochemical modifications that affect their development. Auxins control the process of cell division and maturation. In some crops (maize and rice) enhanced auxin-related gene expression aligns with genome activation, which occurs soon after fertilization (Chen *et al*., 2017, Matilla, 2020). The growth of the endosperm, seed coat, and embryo is coordinated by cytokinins, auxins, and GAs. Auxin is ubiquitous throughout the seed-forming process and abnormalities have been noticed in embryogenesis in mutants lacking auxin functions. The concentration of auxin affects seed development, which is important for ovule fertilization, the development of embryos, and determining the polarity of the developing embryo (Robert *et al*., 2018, Locascio *et al*., 2014). The understanding of auxin's function in seed dormancy dates back to the twentieth century when its significance was identified in connection with its function in plant development. Cell elongation as well as tropic responses were the primary focus of early research, but its impact on the seed physiology was ignored. Auxin's role was observed to alter germination in the middle of the 20th century, which prompted investigations that auxin might delay germination. Hormone interactions such as ABA, IAA, GA, and JA increase the complexity of the regulation of dormancy while the advancements in molecular biology techniques have identified specific genes and proteins that regulate auxin pathways, such as PIN proteins for transport and YUCCA genes for biosynthesis, providing insights into the regulation of dormancy (Tognacca *et al*., 2024, Jhanji *et al*., 2024). Additionally, recent research has revealed the molecular pathways that underlie IAA association with other hormones to modulate seed dormancy, ABA, GA, and jasmonic acid (JA).

Furthermore, it has been revealed that there is compelling evidence connecting IAA mode of action and plant development with ABA. These hormones probably evolved together and interact with one another evolutionarily. On the other hand, very little is known about auxin's (IAA) function in late seed development. Based on several reports, IAA is derived from tryptophan and is controlled by several different pathways. In connection to our previous discussion, IAA biosynthesis is essential for processes such as embryogenesis in seeds (Matilla, 2020) and its elevated amounts signify its pivotal role in signaling during seed development. Recently some of the researchers demonstrated that auxin and ABA work together to promote seed dormancy, emphasizing auxin's function in ABA signaling. According to Liu *et al*., (2013) auxin signaling or biosynthesis increases significantly boost seed dormancy, disruption in IAA signaling in MIR160-overexpressing seeds, auxin receptors mutants, or auxin biosynthesis mutants rapidly release seed dormancy. The roles of IAA and ABA in seed dormancy are linked, as auxin action during seed dormancy depends upon the ABA signaling cascade. Additionally, they demonstrated that IAA stimulates the auxin response elements AUXIN-RESPONSE-FACTOR-10 (ARF10) and AUXIN-RESPONSE-FACTOR-16 (ARF16) to control the expression of ABI3 in seed germination, acting upstream of the primary regulator of seed dormancy, ABI3. Thus, they described a previously unknown regulatory component of seed dormancy in addition to the network that coordinates IAA and ABA signaling during this essential stage.

More recently, Mei *et al*., (2023) revealed that IAA combined with jasmonic acid (JA) enhances ABA's potential to delay seed germination. They confirmed that JA-promoted ABA responses are dependent on IAA, in which JA-induced ABA responses are aided by the interaction between certain transcription factors ARF-10 and ARF-16 and JA signaling repressors (Jasmonate Zim Domain-JAZ). In plants with JA defective signaling, overexpression of ARF-16 partially recovers the phenotype. Moreover, ABI5, a crucial regulator of ABA signaling, interacts with ARF-10 and ARF-16. It is through ABI5 that ARF-16 can improve JA-mediated ABA responses. Thus, JAZ repressors block the ability of ARF10/16 to activate the transcriptional function of ABI5. Based on the discussion above, IAA plays a vital role in multiple stages of seed development, particularly endosperm development and embryogenesis. Likewise, seed dormancy is positively influenced by IAA and is regulated by ABA-mediated signaling. However, a delicate balance among the levels of different plant hormones is not only evident during the early, mid, and late stages of seed development but IAA and GA greatly modulate seed germination.

IAA's role in the dormancy of seeds remains a subject of disagreement and conflicting conclusions due to studies delivering inconsistent results or interpretations, which led to ongoing discussion and more research in this domain. One of the main points of controversy includes auxin's multiple effects on seed dormancy. While some studies argue that auxin stimulates dormancy release or germination, others indicate that it endorses dormancy induction or maintenance. Auxin treatments can have different results depending on a variety of experimental variables, including seed species, hormone concentrations, and environmental factors. These variations could be the cause of this discrepancy. Regarding the processes behind IAA-mediated modulation of seed dormancy, contradictory results have also been reported. IAA modulates hormone crosstalk and the expression of genes patterns linked to dormancy and germination, according to certain studies, however, other research has not found any evidence of significant alterations in IAA-related mechanisms or gene expression patterns in response to IAA treatments. The relationship between IAA and other hormones, especially ABA, which is essential for seed dormancy, is another subject of conflict. According to some research, IAA may work with ABA to control dormancy status, while other findings argue that IAA opposes ABA-induced dormancy and stimulates germination. These divergent results highlight the complex interaction between the ABA and IAA signaling pathways and the context-specific nature of hormone regulation during seed dormancy.

IAA's role in seed germination: A wide range of factors (including water, temperature, light, phytohormones, etc.) impact different stages of the complicated process of seed germination. When seeds are subjected to the right combination of moisture and temperature, they begin to actively undergo metabolism and germinate. At first, water permeates through the seed coat and triggers enzymatic activities that release stored nutrients, including proteins and starches, from the seed into simpler forms that the developing embryo can use. This stage of hydration is very important because it allows the seed coat to become softer and starts the metabolic process that produces energy and allows cells to respire. After getting some water, the embryo grows again, stretching and subsequently breaking the seed coat. The start of germination can be determined by this emergence. However, hormonal regulation plays a role in this process and it has been demonstrated that IAA plays a key role in the initial stages of germination (Ljung *et al*., 2001, Slavov *et al*., 2004). Besides this, many physiological processes, such as apical dominance, tropisms, shoot elongation, stimulation of cell division, and lateral root initiation, are linked to IAA, and IAA content in plant tissue is thought to be controlled by several mechanisms. While the exact mechanism and biosynthesis of IAA in a plant's growth and development are still not fully understood there are reasons to believe that several pathways are involved in IAA synthesis and mechanism of action (Bartel, 1997, Ljung *et al*., 2001).

Recently, it has been reported that IAA regulates seed germination by arranging various developmental processes pivotal for seedling establishment and plants produce active IAA both by de novo synthesis and by releasing IAA from different conjugates. Due to this variability, there is currently no clearly defined mechanism for IAA production in plants. Genetic and biochemical investigations have shown both tryptophan (Trp)-dependent and tryptophan (Trp)-independent pathways for IAA production in plants (Bartel, 1997, Solanki & Shukla, 2023). The ultimate synthesis of IAA in plants is determined by both pathways working together. The chorismate pathway in chloroplasts is the primary source of Trp in plants that are involved in the tryptophan-dependent pathway. The chorismate pathway's intermediate product, indole glycerol phosphate (IGP), is used by the tryptophan-independent pathway to produce IAA instead of requiring Trp (Solanki & Shukla, 2023). Moreover, reactive oxygen species (ROS) also accumulate in seeds to a degree that positively regulates seed germination and it is proposed that ROS upregulate ABA catabolism and promote GA biosynthesis to maintain a dynamic balance between GA and ABA during seed germination (Fig. 1).

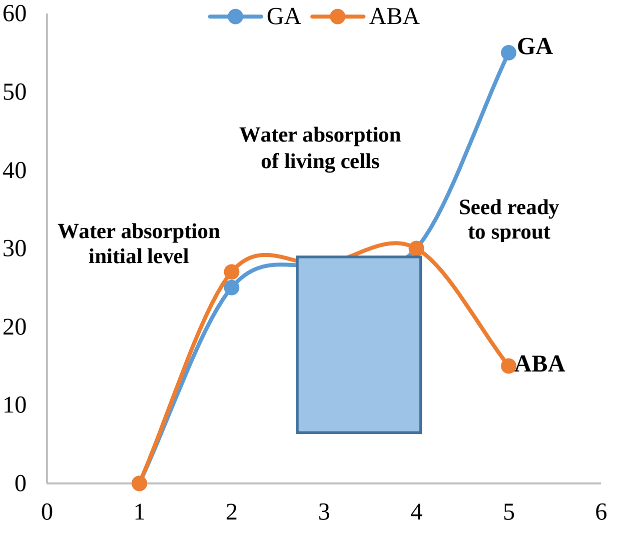

Fig. 1. Shows seed sprouting and levels of ABA and GA in combination with water absorption.

More recently, the study of Hussain *et al*., (2020) revealed a novel function of the auxin signaling repressor Aux/IAA8 during seed germination. They concluded that IAA8 accumulated to high levels during seed germination, which was achieved not only by increased protein synthesis but also by the stabilization of IAA8 protein. They also showed that IAA8 down-regulates the transcription of ABSCISIC ACID INSENSITIVE3 (ABI3), a negative regulator of seed germination and suggested that the auxin signaling repressor IAA8 acts as a positive regulator of seed germination in *Arabidopsis thaliana* (Hussain *et al*., 2020). Furthermore, the study of Raja *et al*., (2021) revealed that nanofibers developed from biodegradable polymer polyvinyl alcohol (PVA) were infused with plant growth promoting hormones (GA3 and IAA) and was characterized using SEM and UV–Vis spectroscopy. The UV–Vis spectra revealed that IAA incorporated nano-fiber-coated seeds such as groundnut and black gram had higher germination and seedling vigor. On the other hand, the study of Liu *et al*., (2013) revealed that auxin controls seed dormancy through stimulation of ABA. However, there are specific expressions of IAA in regulation of seed germination and sensitivity of IAA concentration that varies among different plant species.

In a recent study, Zhang *et al*., (2021) revealed a rice Aux/IAA protein (OsIAA20) for its pragmatic role in seed germination and abiotic stress tolerance. They investigated the role of OsIAA20, which was up-regulated by abiotic stress conditions and exogenous ABA treatment and concluded that OsIAA20 contributes positively to abiotic stress tolerance that enhances growth in different developmental stages, reduces water loss, enhance seed germination. Furthermore, the study of Zhong *et al*., (2023) demonstrated that IAA content increased significantly in different stages of *Bretschneidera sinensis* seed germination, and at the end of seed germination IAA content was 14 fold higher than initial value. This shows that IAA plays a positive role in inducing seed germination. Nonetheless, germination of seeds do not solely depends on the increase or decrease of a single hormone level such as IAA, ABA, or GA. Because a spatiotemporal balance of IAA, ABA, and GA is prerequisite for determining seed germination capability. In a recent research, Zhao *et al*. (2020) examined IAA as a seed priming agent in *Gossyoium hirsutum* L. to investigate its role in the seed germination, seedling growth and its effect on soluble sugar content. They revealed that IAA priming enhanced the rate of cotton seeds germination by controlling the endogenous phytohormones where endogenous ABA contents were decreased while endogenous IAA and GA contents were increased. They investigated germination rate, average germination time, and mean daily germination index for seeds with and without IAA priming treatment and reported that daily germination index and daily germination rates were significantly higher compare to control throughout one week of germination experiment. Moreover, endogenous IAA, GA, and ABA contents were assessed during seed germination. It was demonstrated that the IAA priming treatment considerably augmented the endogenous IAA content in cotton seedlings that were germinating for the duration of the germination phase compared to the control. Additionally, on the first day of germination, the IAA content in the IAA priming treatment reached its highest level. In connection to this, many research groups are keenly interested in screening of plant growth promoting bacteria (PGPB) with IAA producing capability from extreme environmental conditions to evaluate its role in seed bio-priming and germination.

Role of IAA-producing plant growth promoting rhizobacteria (PGPR) in seed Bio-priming: Seed bio-priming refers to the use of PGPR in seed coating or pelleting to enhance seed germination, seedling vigor and to mitigate environmental stress conditions (Fiodor *et al*., 2023). Bio-priming stimulates the seed's inactive metabolic pathways, which stimulates the growth and development of seedlings at their earliest stages (Fig. 2). According to Rakshit *et al*., (2015) bio-priming provides many benefits over conventional seed treatments, such as improved disease resistance, increased nutrient uptake, and decreased dependency on artificial chemicals (Mitra *et al*., 2021). It does this by utilizing the symbiotic interactions that naturally exist between seeds as well as beneficial microbes. Seed bio-priming offers an array of applications in agriculture, encompassing different agricultural systems and adverse environmental conditions (Chakraborti *et al*., 2022; Moon & Ali, 2022). Bio-priming enhances stand establishment and better-synchronized emergence by increasing seed germination rate and uniformity (Reddy & Reddy, 2013). This is especially helpful in unfavorable environmental situations where seeds can find it difficult to germinate and grow, including salinity, low soil fertility, and drought. In addition, bio-priming can improve seedlings' vigor and root growth, resulting in healthier, stronger plants that are more resilient to environmental challenges like salinity, heat, and cold (Rajendra Prasad *et al*., 2016). Furthermore, protecting against soil-borne infections and pests through bio-priming with particular microbial strains might lessen the need for chemical-based pesticides and encourage environmentally friendly pest control strategies (Sooda *et al*., 2020, Mondala *et al*., 2022).

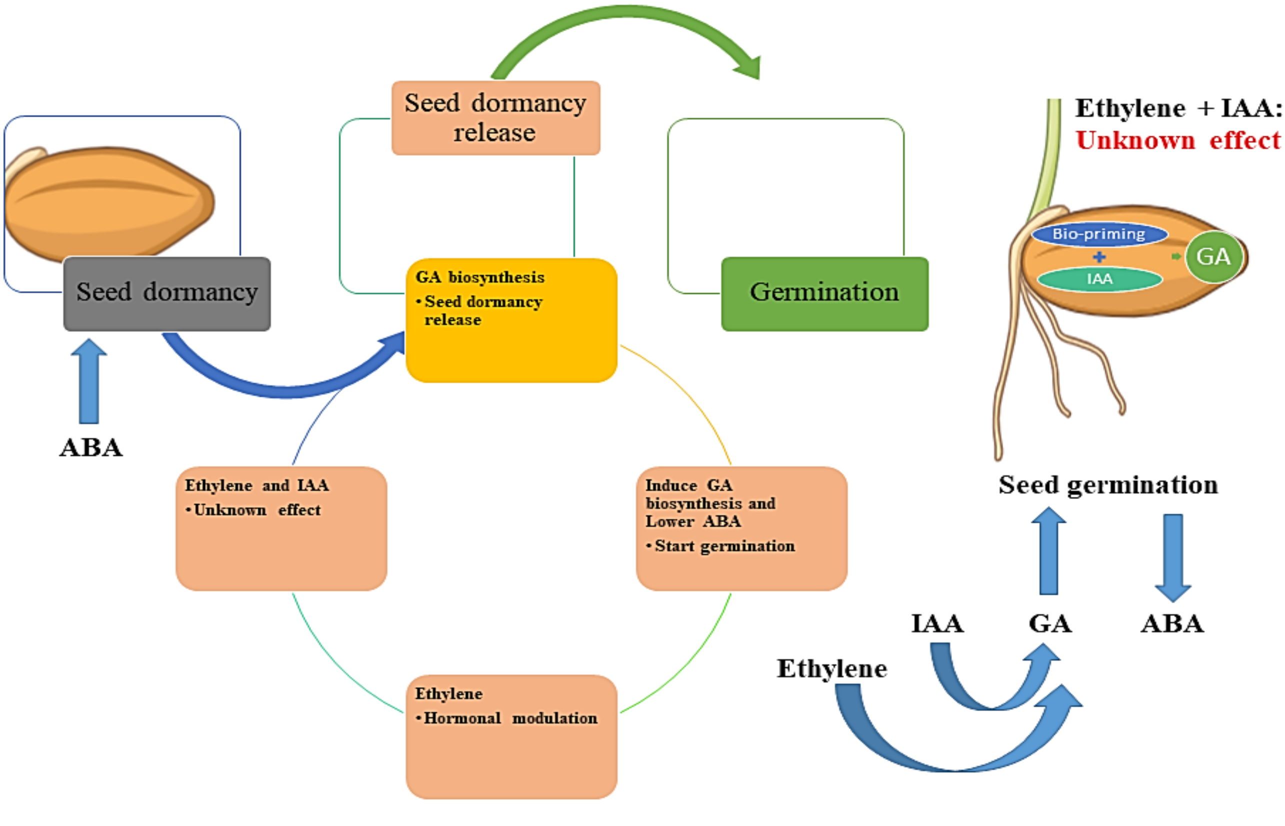

Fig. 2. Bio-priming effect on the growth and development of seedlings at their earliest stages and hormonal modulation.

Research on the role of IAA-producing PGPR in seed bio-priming is an exciting field essential to crop productivity and sustainable agriculture. Various researchers reported the importance of IAA-producing PGPR and their role in the germination of seeds, seedling growth, and overall plant development. In a bio-priming experiment, Fiodor *et al*., (2023) reported soaked carrot seeds that were placed on Whatman paper soaked with the same bacterial suspension, where the addition of the bacterial suspension was to support the colonization process and increase the number of cells adhering to the seeds. They reported that by comparing control with *S. marcescens* AF8I1 significantly improved the relative seed germination (156.88 ± 2.35%). Furthermore, carrot seeds inoculated with different bacteria augmented seed germination i.e., *Pseudomonas fluorescens* AF8I4 (125.64 ± 12.1%), *Pseudomonas putida* AF1I1 (116.8 ± 1.11%), *Klebsella aerogenes* (AF3II1 115.9 ± 2.67%), and *Bacillus cereus* AF8II13 (115.28 ± 2.56%). They concluded that IAA are mainly involved in the seed germination which was produced by IAA-producing PGPR. Similarly, the study of Siraj *et al*., (2022) revealed that *Microbacterium oxydans* (AGH3) is actively involved in the synthesis of IAA, GA, and the solubilization of phosphate, and it can stimulate the growth and development of plants. Moreover, *M. oxydans* showed potential in improving plant development attributes at the physiological, biochemical, and molecular levels as well as alleviating the damage caused by drought stress in *Solanum lycopersicum*. In a more recent study, Shaffique *et al*., (2023) revealed seed bio-priming of wheat with a novel rhizobacterial strain *Klebsiella aerogenes* SH-8 isolated from the rhizosphere of *Artemisia vulgaris*. It was reported that the rhizobacterial strain enhances plant resistance to drought and displays plant growth promoting characteristics, including resistance to oxidative stress and IAA synthesis. They also came to the conclusion that strain SH-8 considerably increased plant biomass and that its inoculation enhanced plant germination metrics.

Based on the above discussion, it can be concluded that IAA-producing PGPRs enhance seed vigor and improve seedling establishment through a variety of physiological and biochemical mechanisms in the bio-priming procedure (Khan *et al*., 2016). Hormone signaling pathway modulation is one of the main mechanisms by which IAA-producing rhizobacteria stimulate seed germination. IAA facilitates the release of dormancy and the start of germination by interacting with plant hormones including ABA and GAs. Furthermore, IAA facilitates the absorption and assimilation of nutrients, supplying vital resources for the growth and development of seedlings. Additionally, rhizobacteria that produce IAA can strengthen the resistance of germinating seeds and newborn seedlings by inducing systemic resistance against infections and environmental stressors. However, only certain bacterial strains are capable of enhancing seed germination i.e., bio-priming the seeds of *Cuscuta campestris* with *Bacillus* sp. had no significant effect on seed germination (Sarić-Krsmanović *et al*., 2017). Variations in experimental designs and data interpretation, along with the complexity of seed germination management involving numerous genetic, physiological, as well as environmental variables, can give rise to controversies. Inconsistencies in experimental results and interpretations can be caused by a variety of seed types, growth conditions, and methods, making it difficult to draw definitive conclusions about the involvement of IAA-producing PGPRs in seed biology.

Influence of IAA-producing PGPRs on seed biology: The dynamic interaction between rhizobacterium and IAA on seed biology has a significant impact on seed biology and overall growth and development of the plant. The augmented amount of IAA enhance seed germination and the higher concentration of IAA in the rhizosphere, enhancing root growth, and facilitating nutrient uptake (Pal *et al*., 2019, Shin & Han, 2022). However, this effect should be considered as seed and PGPR specific, as some IAA-producing PGPR inhibit seed germination (Tabatabaei *et al*., 2016, Gul *et al*., 2022). Furthermore, PGPR colonization of seeds surfaces and root tissues enables plants to develop systemic resistance mechanisms capable of protecting early seedlings and germinating seeds from hostile conditions and pathogens. The synergistic effects of IAA and rhizobacteria with plant growth promoting traits on the regulation of hormones, nutritional enhancement, and tolerance to stressful mechanisms further highlight their joint influence on seed biology (Fig. 2).

In a recent study, Pal *et al*., (2019) reported the effectiveness of cadmium-tolerant, IAA-producing PGPRs (*Pseudomonas putida* and *Lysini bacillus*) on *Brassica nigra* L. growth under stressful conditions by comparing it with exogenously applied synthetic IAA. Plant growth in soil treated with Cd was considerably enhanced by the external application of synthetic IAA. On the other hand, when compared to the application of synthetic IAA, PGPR inoculation demonstrated a considerable increase in the plant growth promoting attributes, and other growth indices of Cd-stressed Brassica plants. The growth and development of plants are significantly impacted by the complicated regulatory network that exists between IAA signaling pathways and IAA produced by rhizobacteria. A thorough understanding of this complex interaction can help to promote our understanding for environmentally friendly farming procedures, could improve crop yield under optimize the procedure for seed bio-priming. A comprehensive research is required to fully understand the molecular mechanisms governing this integration and the resulting implications for seed biology and plant health.

Conclusion and Future prospects

Seed dormancy and germination are crucial for plant propagation and survival, allowing adaptation to different environments. Dormancy lets seeds delay germination until conditions are ideal, maximizing survival and reproduction chances by avoiding unfavorable seasons or conditions. Dormant seeds can stay in the soil, avoiding competition and grasping opportunities to colonize new habitats. IAA interacts with ABA to regulate seed dormancy, ensuring germination in favorable conditions. Seed bio-priming with IAA-producing PGPRs, enhances seedling vigor and stress resilience in agriculture. This method triggers physiological changes, improving nutrient uptake and crop productivity. Bio-priming reduces reliance on agrochemicals, promoting sustainable agriculture.

The utilization of IAA and PGPR bio-priming's synergistic effects has profound consequences for sustainable agriculture and seed treatment approaches. Integrating these strategies reduces the need for synthetic agrochemicals and minimizes the negative effects on the environment while enhancing crop productivity and the growth of seedlings in a natural and environmentally friendly approach. Bio-priming techniques can increase the effectiveness of nutrient uptake, encourage stress tolerance, and improve overall plant vigor by utilizing the characteristics of rhizobacteria that promote plant growth and the regulatory roles of IAA in seed germination. Understanding plant-microbe interactions in agricultural settings is crucial, as evidenced by the possible mutual benefits of IAA and rhizobacterial bio-priming on seed germination and dormancy. Nonetheless, additional investigation is required to clarify the precise processes behind these synergistic effects and to enhance bio-priming tactics for various seed types. Integrating plant physiology, microbiology, and agronomy optimizes seed treatments, enhancing agricultural productivity sustainably. Collaboration across disciplines drives innovation for efficient, eco-friendly practices, crucial for advancing seed biology and agricultural sustainability in changing climates.

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