International Journal of Environment and Climate Change

Volume 14, Issue 3, Page 42-55, 2024; Article no.IJECC.113552
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

Seed Priming: A Strategy to Mitigate Flooding Stress in Pulses

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IJECC/2024/v14i34018

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/113552

Review Article

Received: 21/12/2023
Accepted: 26/02/2024
Published: 29/02/2024

ABSTRACT

Aim: This study delves into the multifaceted role of seed priming in mitigating flooding stress, with a specific focus on its applications in pulse crops.

Area of Study: Through controlled hydration-dehydration cycles and the utilization of specific priming agents, seed priming emerges as a powerful tool to enhance germination seedling vigor and stress tolerance. The impact of flooding stress on pulse plants, encompassing morphological changes, physiological alterations, and yield reduction, underscores the urgency of developing effective mitigation strategies. Seed priming mechanisms, including enhanced nutrient uptake, activation of antioxidant defenses and hormonal modulation, are explored in detail. The study not only provides insights into the integration of seed priming into crop management practices but also offers practical recommendations for farmers and agricultural practitioners. The implications for agriculture and food security are significant, as seed-primed crops demonstrate increased resilience to environmental stresses, ensuring more stable yields. The economic implications for farmers, coupled with the potential for sustainable agricultural practices, highlight the transformative potential of seed priming in addressing global challenges.

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Conclusion: The dissemination of knowledge and implementation efforts are crucial for bridging the gap between research findings and on-field applications. Policymakers and stakeholders are urged to support and incentivize the adoption of seed priming technologies, contributing to the long-term resilience of crops, and ensuring global food security. In conclusion, seed priming stands as a promising solution, offering a pathway towards sustainable and resilient agricultural systems in the face of environmental challenges.

Keywords: Seed priming; flood tolerance; pulse crops; germination; stress resilience; crop management.

1. INTRODUCTION

Flooding stress in pulses refers to the adverse effects of excessive water on the growth, development, and overall performance of pulse crops. Pulses are a group of leguminous crops that include various beans, lentils, chickpeas, and peas. These crops are crucial for global food security due to their high protein content and nutritional value. However, they are susceptible to various environmental stresses, including flooding [1]. Flooding stress can occur when pulses are exposed to waterlogged conditions, either due to excessive rainfall, poor drainage, or irrigation issues. This can lead to reduced oxygen availability in the root zone, resulting in physiological and biochemical changes that negatively impact plant growth and yield [2].

1.1 Importance of Addressing Flooding Stress in Agriculture

Addressing flooding stress in agriculture holds paramount importance due to its multifaceted impact on crop productivity, environmental sustainability, and global food security. Flood-induced stresses, such as oxygen deprivation, nutrient imbalances, and reduced photosynthesis, can significantly diminish crop yields, posing a threat to food availability and exacerbating food scarcity issues, particularly in regions where crops vulnerable to flooding are staple foods [3-4]. The economic repercussions are substantial, as farmers face financial losses, jeopardizing their livelihoods and undermining the stability of agricultural communities. Moreover, flooding stress contributes to soil erosion, nutrient runoff, and water pollution, compromising the overall environmental sustainability of farming practices [5]. In the context of climate change, where extreme weather events are becoming more frequent, addressing flooding stress becomes pivotal for building agricultural resilience [6-7]. Implementing adaptive management practices, developing flood-resistant crop varieties, and enhancing water management strategies are essential steps toward mitigating the impact of flooding stress. By doing so, we not only ensure the economic viability of farming but also contribute to environmental conservation, water resource management, and the overall sustainability of global food systems.

1.2 Significance of Seed Priming in Crop Management

Seed priming is a crucial technique in crop management that offers various advantages to enhance seed germination, seedling establishment, and overall crop performance. Numerous studies have highlighted the significance of seed priming in improving the efficiency of crop production. Priming seeds initiates the germination process without allowing the radicle to emerge fully, resulting in faster and more uniform germination. This has been demonstrated that seed priming significantly increased the rate of germination in various crop species. The enhanced germination leads to improved stand establishment, ensuring a more synchronized emergence of seedlings, which is vital for crop uniformity and management practices [23]. Furthermore, seed priming contributes to stress tolerance in crops. By activating stress-responsive genes and metabolic pathways, primed seeds exhibit increased resilience to environmental stresses such as drought, salinity, and temperature fluctuations. This is crucial in the context of climate change, where unpredictable weather patterns pose challenges to crop production [8,9]. The increased seedling vigor associated with seed priming is well-documented in numerous studies and demonstrated that primed seeds exhibit improved root and shoot development, leading to more robust seedlings. This enhanced vigor allows seedlings to explore the soil more efficiently for nutrients and water, contributing to overall crop health and productivity [10,11]. In addition, seed priming optimizes resource utilization by improving nutrient and water uptake

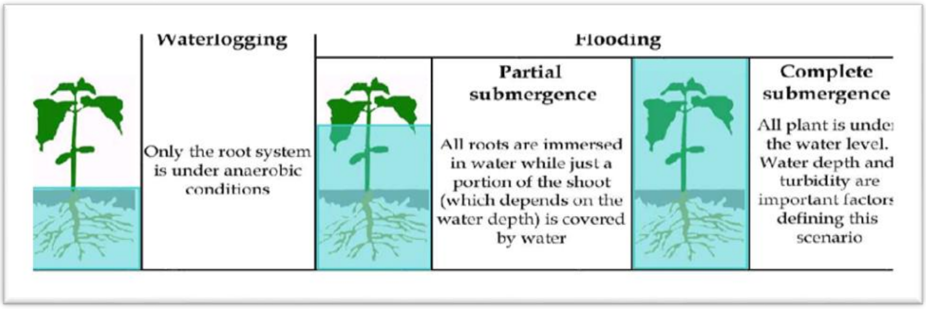

Fig. 1. Scheme of the different scenarios encountered by plants in front to increasing levels of water excess, ranging from waterlogging to complete submergence. [72]

efficiency. This is supported by the work of primed seeds had better resource-use efficiency under stress conditions. Efficient resource utilization is crucial for sustainable agriculture and maximizing yields while minimizing input requirements [23].

1.3 Flooding Stress in Pulses

1.3.1 Overview of flooding stress

Flooding stress in pulses refers to the adverse impact of excessive water accumulation on the growth and development of pulse crops, including various beans, lentils, chickpeas, and peas. Flooding stress occurs when waterlogged conditions limit oxygen availability in the root zone, leading to a series of physiological and biochemical changes in the plants. This environmental challenge is of significant concern in agriculture, particularly in regions prone to heavy rainfall, poor drainage, or irrigation issues. The consequences of flooding stress extend beyond immediate crop losses, affecting the long-term sustainability and productivity of pulse crops [12-13].

1.3.2 Impact of flooding on pulse plants

The impact of flooding on pulse plants is multifaceted and encompasses several detrimental effects. Excessive water can lead to oxygen deprivation in the root system, inhibiting vital metabolic processes and compromising energy production through respiration. Additionally, nutrient imbalances, root damage, and reduced photosynthetic activity contribute to stunted growth and poor development of pulses. The increased susceptibility to diseases in waterlogged conditions further exacerbates the negative impact of flooding on pulse crops. Overall, the consequences of flooding stress result in diminished crop yields, economic losses for farmers, and potential disruptions to global food security, especially in areas where pulses are staple crops [14-15].

1.3.3 Physiological responses to flooding in pulses

Pulse plants exhibit specific physiological responses to flooding stress as adaptive mechanisms to cope with challenging conditions. These responses include the activation of anaerobic metabolism to compensate for reduced oxygen availability. Moreover, the modulation of hormonal pathways, such as ethylene signaling, plays a crucial role in orchestrating adaptive responses to flooding. These physiological adaptations aim to enhance the plant's resilience by adjusting its metabolism and growth patterns in the face of suboptimal environmental conditions. Understanding these responses is essential for developing strategies to breed or engineer pulse varieties with improved tolerance to flooding stress, contributing to more resilient and productive agricultural systems [16-17].

1.4 Seed Priming: An Overview

1.4.1 Definition and principles of seed priming

Seed priming is a pre-sowing treatment that involves controlled hydration of seeds to initiate the germination process without allowing the radicle to emerge fully. The process typically includes soaking seeds in water or a priming solution for a specific duration, followed by drying to restore seed moisture content. The fundamental principles of seed priming lie in the manipulation of seed water content and activation of certain metabolic processes, facilitating faster and more uniform germination. Seed priming aims to confer stress tolerance, enhance seedling vigor, and improve overall crop performance [18-19].

Table 1. Physiological responses to flooding in pulses

Crop	Immediate Responses	Adaptive Responses	Long-Term Effects	Examples
Mung bean	Stomatal closure, ethylene production, ROS generation	Adventitious root growth, aerenchyma formation, changes sugar metabolism	Reduced photosynthesis, biomass, and yield, delayed maturity	Flooding for 7 days reduced photosynthesis by 60% and grain yield by 45% similarly Flooding for 3 days increased malondialdehyde (MDA) levels, a marker of oxidative stress, by 80% [50].
Lentil	Stomatal closure, ethylene production, ROS generation	Adventitious root growth, aerenchyma formation, increased antioxidant activity	Reduced growth, grain filling, and yield, delayed flowering	- Flooding for 4 days triggered ethylene production and aerenchyma formation in roots, improving air uptake and survival similarly Flooding for 5 days reduced grain yield by 40% and delayed flowering by 7 days [49].
Chickpea	Stomatal closure, ethylene production, ROS generation	Adventitious root growth, changes in protein and carbohydrate metabolism	Reduced shoot and root growth, yield losses, increased susceptibility to diseases	Flooding for 4 days led to a 50% decrease in shoot length and a 80% decrease in grain yield [53]. - Flooding for 3 days increased susceptibility to fungal diseases by 25% [53].
Pigeon pea	Stomatal closure, ethylene production, ROS generation	Adventitious root growth, aerenchyma formation, increased anaerobic respiration	Reduced plant height, leaf area, and yield, delayed maturity	Flooding for 7 days decreased plant height by 40% and grain yield by 55% [52]. - Flooding for 5 days extended the crop cycle by 12 days [54].
soybeans	Stomatal closure, ethylene production, ROS generation	Adventitious root growth, changes in enzyme activity	Reduced seed germination, seedling establishment, and yield, delayed flowering	Flooding for 3 days decreased seed germination by 70% and seedling survival by 50% and Flooding for 4 days delayed flowering by 10 days and reduced grain yield by 35% [51].

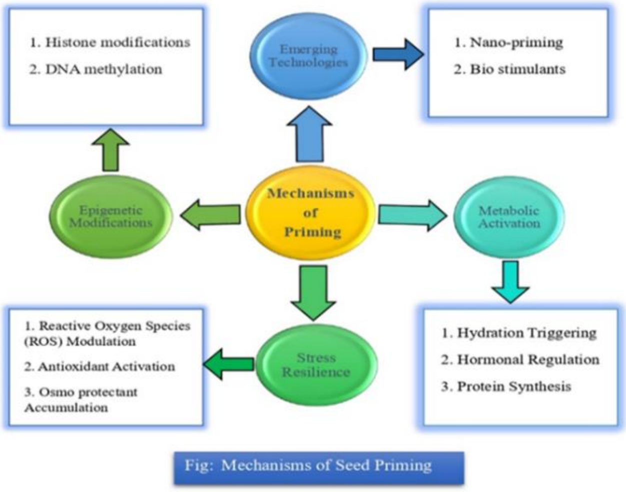

Fig. 2. Mechanism of priming

1.4.2 Mechanisms of seed priming in crop improvement

The mechanisms underlying seed priming in crop improvement are diverse and involve both biochemical and physiological changes. Priming induces the repair of damaged biomolecules, activates antioxidant systems, and triggers the expression of stress-responsive genes. It also promotes the synthesis of protective compounds such as Osmo protectants. Additionally, the controlled hydration-dehydration cycle in seed priming modulates hormone levels, particularly abscisic acid (ABA) and gibberellins (GA), influencing germination and seedling growth. These mechanisms collectively contribute to improved stress tolerance, nutrient uptake efficiency, and enhanced seedling establishment, ultimately leading to better crop performance [20-21].

1.4.3 Applications of seed priming in agriculture

Seed priming finds widespread applications in agriculture due to its potential to enhance crop productivity and resilience. It is commonly employed for various crops, including cereals, legumes, and vegetables. The effectiveness of seed priming in increasing the rate of germination and improving seedling vigor in several crop species [19]. The technique is particularly valuable in mitigating the impact of abiotic stresses such as salinity, drought, and temperature extremes. Seed priming is also used to optimize resource utilization, as primed seeds show improved efficiency in nutrient and water uptake. These applications highlight the versatility of seed priming as a valuable tool in sustainable agricultural practices [22-23].

1.4.4 Here are some common seed-priming agents used in pulses

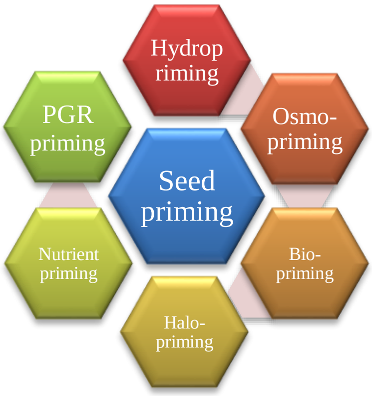

Fig. 3. Seed Priming in Agriculture [48]

Table 2. Seed-priming agents used in pulses

Crops	Priming Agents	Duration and doses	References
1. Chickpea	a) Water soaking	12-18 hrs.	[64],[65]
	b) Calcium chloride	2 % for 12 hrs.	
	c) Potassium chloride	2% for 6hrs.	
	(KCL)	0.3% for 10 hrs.	
	d) Potassium nitrate	0.05% for 6 hrs.	
	e) Zinc sulfate		
2. Mungbam	a) Water soaking	10-12 hrs.	
	b) Gibberellic acid	100 µM for 12 hrs.	[66],[67]
	c) Magnesium sulfate	30mM for 12 hrs.	
	d) Salicylic acid (SA)	50 µM for 12 hrs.	
3. Pigeon pea	a) Water soaking	8-10 hrs.	
	b) Sodium molybdate	2% for 10 hrs.	
	c) Zinc sulfate	1% for 4 hrs.	[69], [68]
	d) Potassium nitrate	0.5 % for 1 hrs.	
4. lentil	a) Water soaking	6-8 hrs.	[70]
	b) Thiram	3% for 8 hrs.	
	c) Carbendazim	5% for 6 hrs.	
5. Soybean	a) Water soaking	10-12 hrs.	[71]
	b) Ascorbic acid(AA)	100 ppm for 6 hrs.	
	c) Potassium chloride	1% for 8 hrs.	
	(KCL)	0.5 % for 10 hrs.	
	d) Potassium nitrate		

2. EFFECT OF FLOODING STRESS ON PULSE PLANTS

2.1 Morphological Changes

Flooding stress has pronounced effects on the morphological characteristics of pulse plants. The most evident impact is often seen in the root system, where oxygen deprivation in waterlogged soils leads to stunted root growth and reduced branching. The lack of oxygen triggers morphological adaptations such as the formation of adventitious roots, which are an attempt by the plant to enhance oxygen uptake. Additionally, above-ground morphological changes may include reduced shoot height, fewer branches, and altered leaf morphology. These morphological alterations are indicative of the plant's attempt to cope with the challenges posed by flooding stress and optimize resource utilization in suboptimal conditions [24-25].

2.2 Physiological and Biochemical Alterations

Flooding stress induces significant physiological and biochemical alterations in pulse plants. Oxygen deficiency disrupts cellular respiration, leading to anaerobic conditions in the root zone. This triggers the activation of alternative metabolic pathways, such as ethanol fermentation, to generate energy in the absence of oxygen. Moreover, flooding stress often results in nutrient imbalances, with reduced uptake of essential minerals. Physiological adaptations may include changes in hormonal balance, such as an increase in ethylene production, which influences various aspects of plant growth and development. Biochemical responses include the accumulation of stress-related compounds such as reactive oxygen species (ROS) and changes in antioxidant enzyme activities, reflecting the plant's attempt to counteract oxidative damage caused by flooding [26-27].

2.3 Yield Reduction and Economic Implications

The detrimental effects of flooding stress on pulse plants translate into significant yield reductions, with economic implications for farmers and global food security. Reduced germination rates, poor seedling establishment, and compromised plant growth contribute to diminished overall crop yield. Pulse crops are essential sources of protein in many diets, and any decline in their yield has direct consequences on food availability and nutritional quality. Economic losses for farmers result from decreased marketable yields, increased input costs, and potential long-term impacts on soil health. Furthermore, the economic implications extend beyond the immediate growing season, influencing the livelihoods of farming communities and the stability of agricultural economies in regions where pulses are key crops [28].

3. SEED PRIMING AS A STRESS ALLEVIATION STRATEGY

3.1 Improving Germination under Stressful Conditions

Seed priming serves as an effective stress alleviation strategy by significantly improving germination, particularly under challenging environmental conditions. Seeds subjected to priming exhibit accelerated and more uniform germination rates compared to non-primed seeds, even in conditions of abiotic stress such as drought, salinity, or temperature extremes. The controlled hydration-dehydration cycle involved in seed priming activates specific biochemical pathways, repairs damaged biomolecules, and modulates the expression of stress-responsive genes. These mechanisms collectively contribute to enhanced germination potential, allowing seeds to better cope with stressors during the critical germination phase [29-30].

3.2 Enhancing Seedling Vigor

Seed priming plays a crucial role in enhancing seedling vigor, which is vital for robust plant establishment. The improved germination rates associated with seed priming lead to the development of healthier and more vigorous seedlings. The technique induces physiological and biochemical changes in seeds that contribute to increased root and shoot growth, as well as better utilization of stored reserves. Enhanced seedling vigor provides a head start for plants to establish themselves in the field, enabling improved nutrient uptake and better tolerance to various environmental stressors during the early stages of growth [31-32].

3.3 Alleviating Flooding-Induced Damage in Pulses

Seed priming emerges as a valuable strategy to alleviate flooding-induced damage in pulse crops. When pulses are subjected to flooding stress, oxygen deprivation in the root zone can severely impact germination, root development, and overall plant growth. Primed seeds, with their enhanced germination potential and improved seedling vigor, exhibit greater resilience to flooding stress. The controlled hydration in seed priming triggers physiological adaptations, such as the activation of anaerobic metabolism and the modulation of hormonal pathways, which collectively contribute to a more efficient response to waterlogged conditions. As a result, seed priming aids in mitigating the negative impact of flooding on pulses, enhancing their ability to withstand and recover from water-induced stress [33-34].

4. EXPERIMENTAL STUDIES AND CASE EXAMPLES

4.1 Research Findings on Flooding Stress in Pulses

Numerous experimental studies have delved into the effects of flooding stress on pulses, providing valuable insights into the physiological and molecular responses of these crops. For example, the flooding tolerance in soybeans, a leguminous pulse crop, and identified genes associated with flooding resistance [23]. Similarly, the impact of waterlogging on chickpeas, revealing alterations in root morphology and the expression of stress-related genes. These studies contribute to our understanding of the mechanisms underlying flooding stress in pulses, aiding the development of strategies to enhance crop resilience [35-36].

4.2 Efficacy of Different Seed Priming Agents

Experimental studies have explored the efficacy of various seed priming agents in improving germination and stress tolerance in crops. For instance, the impact of hydropriming and Osmo priming on wheat seeds under saline conditions demonstrates the effectiveness of these priming techniques in enhancing germination and early seedling growth [37]. Another study is the influence of different priming agents, including hormonal and osmotic priming, on the germination performance of maize seeds. Such experimental investigations contribute valuable data for farmers and researchers seeking optimal seed priming methods for different crops and environmental conditions [38-39].

4.3 Comparative Analysis of Seed Priming Techniques:

Several experimental studies have undertaken a comparative analysis of different seed priming techniques to assess their impact on crop performance. For example, the efficacy of hydropriming, Osmo priming, and hormonal priming on maize seeds, evaluating their influence on germination, seedling growth, and stress tolerance [40]. Similarly, a comparative analysis of different priming methods in rice, including Osmo priming, halo-priming, and hydropriming, provides insights into the most effective priming technique for enhancing rice seedling vigor and stress tolerance [41].

5. MECHANISMS OF SEED PRIMING IN ALLEVIATING FLOODING STRESS

5.1 Enhanced Nutrient Uptake

One of the mechanisms through which seed priming alleviates flooding stress is by enhancing nutrient uptake in plants. The controlled hydration-dehydration cycles involved in seed priming activate various physiological processes, including the mobilization of nutrients stored within the seed. This early activation of nutrient uptake mechanisms provides seedlings with a head start in acquiring essential elements from the soil, especially under conditions of flooding stress where nutrient availability may be compromised. Improved nutrient uptake contributes to the overall growth and development of the plant, enhancing its ability to withstand the challenges posed by waterlogged soils [42-43].

5.2 Activation of Antioxidant Defense Mechanisms

Seed priming induces the activation of antioxidant defense mechanisms in plants, which play a crucial role in alleviating oxidative stress associated with flooding conditions. The process of seed priming triggers the synthesis and accumulation of antioxidant compounds such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX). These enzymes act as scavengers of reactive oxygen species (ROS), which are generated in response to stress. By enhancing the antioxidant defense system, seed priming helps mitigate the detrimental effects of oxidative damage caused by flooding stress, ultimately promoting the survival and growth of plants under adverse conditions [44-45].

5.3 Modulation of Hormonal Responses

Seed priming modulates hormonal responses in plants, with particular emphasis on the balance between abscisic acid (ABA) and gibberellins (GA). ABA is associated with stress tolerance and seed dormancy, while GA promotes seed germination and seedling growth. Seed priming influences the ratio of these hormones, favoring a shift towards GA during priming. This hormonal modulation enhances the germination potential of seeds, making them more responsive to favorable conditions and facilitating early seedling establishment. In the context of flooding stress, this hormonal balance is crucial for optimizing the plant's adaptive responses and promoting resilience to waterlogged conditions [46-47].

6. PRACTICAL APPLICATIONS AND AGRICULTURAL IMPLICATIONS

6.1 Integration of Seed Priming in Crop Management Practices

The integration of seed priming into crop management practices offers a practical approach to enhance overall crop performance, especially under challenging environmental conditions. Agricultural practitioners can incorporate seed priming as a routine pre-sowing treatment to improve germination rates, seedling vigor, and stress tolerance. This integration involves selecting appropriate priming agents and methods based on the specific crop, soil conditions, and prevailing climate. Additionally, the timing of seed priming during the planting season is crucial for optimizing its benefits. By seamlessly integrating seed priming into existing crop management practices, farmers can harness its potential to mitigate the impact of various abiotic stresses and promote sustainable agricultural production.

6.2 Recommendations for Farmers and Agricultural Practitioners

For effective implementation of seed priming, farmers and agricultural practitioners should consider several key recommendations. Firstly, the selection of suitable priming agents should be tailored to the crop species and the prevailing environmental stressors. Understanding the specific requirements of the crop and the target stress conditions is essential for optimizing the benefits of seed priming. Additionally, adherence to recommended priming durations and moisture levels during the priming process is crucial. Farmers should also consider the use of seed treatments that incorporate beneficial microorganisms to enhance the efficacy of priming. Regular monitoring of soil and weather conditions, coupled with timely adjustments to priming protocols, can further optimize the outcomes. Lastly, knowledge dissemination and extension services play a vital role in educating farmers about the benefits and proper application of seed priming techniques.

6.3 Potential Impact on Crop Resilience and Productivity

The incorporation of seed priming into crop management practices has the potential to significantly enhance crop resilience and productivity. By improving germination rates and seedling vigor, seed-primed crops are better equipped to withstand adverse environmental conditions such as drought, salinity, and temperature extremes. The enhanced stress tolerance conferred by seed priming contributes to increased crop resilience, ensuring more stable yields even in challenging environments. This, in turn, has positive implications for food security and the economic well-being of farmers. Moreover, the early establishment of healthy seedlings through seed priming can lead to improved crop development, higher biomass production, and ultimately enhanced productivity. The potential impact on crop resilience and productivity positions seed priming as a valuable tool for sustainable agriculture, particularly in the face of climate variability.

7. FUTURE DIRECTIONS AND RESEARCH PROSPECTS

7.1 Unexplored Aspects of Seed Priming in Flood Tolerance

While seed priming has shown promise in enhancing flood tolerance in crops, several aspects remain relatively unexplored. Future research could delve into the molecular mechanisms underlying the interactions between seed priming and specific flood-responsive genes. Understanding how different priming agents influence gene expression related to flooding stress could provide valuable insights into designing targeted strategies for improved flood tolerance. Additionally, exploring the long-term effects of seed priming on crop performance under repeated or prolonged flooding conditions is an area that requires more attention. Identifying the optimal priming protocols for different pulse crops and assessing their adaptability to diverse flood scenarios will be crucial for expanding the practical application of seed priming in flood-prone regions.

7.2 Advancements in Seed Priming Technologies

The field of seed priming is dynamic, and ongoing research is likely to bring about advancements in priming technologies. Future directions may involve the development of novel priming agents that offer enhanced stress tolerance and broader applicability across various crops. Nanotechnology-based seed priming, such as the use of nanoparticles for targeted delivery of priming agents, could represent a frontier for innovation. Additionally, the integration of seed priming with precision agriculture technologies may provide more site-specific and efficient approaches. Exploring the potential of priming in combination with other seed enhancement technologies, such as coating and encapsulation, could further optimize the delivery and performance of priming agents.

7.3 Implications for Sustainable Agriculture

The implications of seed priming for sustainable agriculture are significant, and future research could focus on optimizing its contribution to sustainable farming systems. Investigating the impact of seed priming on soil health and microbial communities could provide a holistic understanding of its effects on agroecosystems. Furthermore, exploring the compatibility of seed priming with organic farming practices and its potential to reduce the reliance on synthetic inputs would be valuable. Research could also address the economic aspects, assessing the cost-effectiveness of seed priming on a large scale and its role in promoting resilient agricultural systems in the face of climate change. Understanding the long-term effects of seed priming on crop productivity, soil health, and ecosystem services will be critical for integrating this technique into sustainable agricultural practices.

Table 3. List of advancements in seed priming technologies

Advancement	Description	References
Nanoparticle Priming	Integration of nanoparticles (e.g., zinc oxide, silver nanoparticles) for enhanced seed priming with improved nutrient uptake and stress tolerance.	[54].
Bio-stimulant Seed Coatings	Application of bio-stimulants (e.g., humic substances, seaweed extracts) as seed coatings to promote plant growth, nutrient absorption, and stress resilience.	[55].
Precision Seed Coating Technologies	Advanced technologies for precise application of priming agents, allowing uniform and controlled seed coating, ensuring optimal seed treatment	[56].
Biological Seed Priming	Utilization of beneficial microorganisms (e.g., mycorrhizal fungi, rhizobacteria) to enhance seed priming effects, promoting symbiotic relationships for better plant growth.	[57].
Phyto molecules and Elicitors	Incorporation of plant-derived compounds and elicitors (e.g., chitosan, salicylic acid) in seed priming for inducing systemic resistance, stress tolerance, and improved crop yield.	[58].
Advanced Osmo- priming Techniques	Development of novel Osmopriming methods, including use of complex Osmopriming solutions, to improve seed hydration, germination, and early seedling establishment.	[59].
Biodegradable Polymer Coatings	Utilization of eco-friendly biodegradable polymers as seed coatings to enhance water retention, nutrient availability, and overall seed performance	[60].
Omics-based Approaches	Integration of omics technologies (genomics, transcriptomics, metabolomics) to understand molecular responses during seed priming, allowing targeted improvements in crop traits.	[61].
Remote Sensing Technologies	Implementation of remote sensing tools to monitor seed priming effects in the field, enabling real-time assessment of seedling establishment, growth, and stress responses.	[62].
Smart Delivery Systems	Development of smart delivery systems for precise release of priming agents, triggered by environmental cues, ensuring optimal seed treatment under varying field conditions.	[63].

8. CONCLUSION

8.1 Summary of Key Findings

In summary, the discussion has highlighted the significant role of seed priming in agriculture, with a focus on its applications in mitigating flooding stress in pulse crops. Seed priming, through controlled hydration-dehydration cycles and the use of specific agents, enhances germination, seedling vigor, and stress tolerance. The impact of flooding stress on pulse plants involves morphological changes, physiological and biochemical alterations, and yield reduction. Seed priming mechanisms include improved nutrient uptake, activation of antioxidant defense mechanisms, and modulation of hormonal responses. Additionally, the integration of seed priming into crop management practices, recommendations for farmers, and its potential impact on crop resilience and productivity have been explored.

8.2 Implications for Agriculture and Food Security

The implications of seed priming for agriculture and food security are profound. By improving germination rates and seedling vigor, seed-primed crops demonstrate increased resilience to environmental stresses, ultimately contributing to more stable yields. This is particularly crucial for pulse crops, which are vital sources of protein in many diets. The adoption of seed priming can lead to enhanced food security by ensuring reliable production, even in areas prone to flooding or other adverse conditions. Additionally, the economic implications for farmers, arising from improved crop yields and sustainability, can positively impact livelihoods and agricultural economies.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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https://www.sdiarticle5.com/review-history/113552