Review Article

Optimizing Agriculture: A Review of Chemical Priming in Crop Production

Abstract:

Agricultural productivity faces increasing challenges due to climate change, soil degradation, and the need for sustainable practices. Chemical priming, a technique involving the pre-treatment of seeds or plants with specific compounds, has emerged as a promising approach to enhance crop resilience, productivity, and stress tolerance. This review synthesizes current literature on the application of chemical priming in crop production, focusing on its mechanisms, effects on plant physiology, and its potential to optimize agricultural practices. Chemical priming operates through diverse mechanisms, including the induction of stress-responsive genes, enhancement of antioxidant activity, and modulation of hormone signaling pathways. These mechanisms result in improved germination rates, accelerated seedling growth, increased nutrient uptake, and enhanced tolerance to various abiotic and biotic stresses. Moreover, chemical priming has been shown to promote crop yield and quality under adverse environmental conditions, making it a valuable tool for sustainable agriculture. The effectiveness of chemical priming depends on various factors, such as the type of priming agent, concentration, timing of application, and the specific crop species. Furthermore, interactions with other agricultural practices, such as irrigation regimes and fertilization strategies, can influence its outcomes. Therefore, optimizing chemical priming protocols requires a comprehensive understanding of crop-specific responses and environmental factors. Despite its potential benefits, the widespread adoption of chemical priming in agriculture faces challenges related to cost-effectiveness, regulatory approval, and potential ecological impacts. Addressing these challenges requires further research to refine priming protocols, assess long-term effects on soil health and ecosystem functioning, and develop sustainable approaches for large-scale implementation.

Keywords. Chemical priming, Molecular mechanism, Applications

Introduction.

Chemical priming has emerged as a pivotal technique in modern agricultural practices, revolutionizing crop production methodologies. Through the strategic application of various chemical compounds, this approach induces physiological and biochemical changes in plants, enhancing their resilience to environmental stresses and improving overall yield. A plethora of studies, including those by Khan [1], Smith and Jones [2], and Patel [3] have underscored the efficacy of chemical priming in augmenting crop performance under adverse conditions. The concept of chemical priming revolves around the manipulation of plant defense mechanisms to bolster their adaptive capacities. By triggering specific pathways involved in stress response, priming agents such as salicylic acid (SA), methyl jasmonate (MeJA), and hydrogen peroxide (H2O2) stimulate the synthesis of defense-related proteins and metabolites. Research by Gupta and Sharma and Wang [4,5,6] has elucidated the intricate signaling networks activated by these compounds, elucidating their role in fortifying plants against biotic and abiotic stresses. Furthermore, chemical priming has garnered attention for its ability to enhance nutrient uptake and utilization efficiency in crops. Through the modulation of root architecture and activity, priming agents facilitate the assimilation of essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K). Studies conducted by Singh, Chen and Wu [7,8] have demonstrated the positive impact of chemical priming on nutrient acquisition, highlighting its potential to mitigate nutrient deficiencies and improve crop productivity. In addition to stress mitigation and nutrient management, chemical priming offers a sustainable solution to challenges posed by climate change and environmental degradation. By conferring resilience to heat, drought, and salinity stresses, primed plants exhibit enhanced tolerance to adverse environmental conditions. This aspect has been extensively explored in research by Rahman, Zhang and Li[9,10] emphasizing the role of chemical priming in climate-smart agriculture and sustainable food production. Moreover, the application of chemical priming holds promise for reducing the reliance on agrochemical inputs and minimizing environmental risks associated with conventional farming practices. By enhancing plant defense mechanisms, primed crops exhibit reduced susceptibility to pests and diseases, thereby decreasing the need for synthetic pesticides and fungicides. Notable contributions from studies by Ali, Wang and Liu [11,12] have highlighted the potential of chemical priming as an eco-friendly alternative for pest and disease management in agriculture. Chemical priming represents a cutting-edge approach for optimizing agriculture by harnessing the innate capabilities of plants to withstand environmental stresses and maximize productivity. The collective findings from research endeavors by numerous scholars underscore the multifaceted benefits of chemical priming in crop production, ranging from stress tolerance and nutrient enhancement to sustainability and environmental stewardship. As the agricultural landscape evolves amidst global challenges, the integration of chemical priming holds immense potential for fostering resilient and sustainable food systems worldwide.

Understanding Chemical Priming: A Primer

Chemical priming, a phenomenon wherein exposure to certain chemicals enhances an organism's response to subsequent stimuli, has garnered substantial attention across various scientific disciplines. This primer aims to elucidate the intricacies of chemical priming, drawing upon a vast array of scholarly references to provide a comprehensive understanding. Chemical priming encompasses a diverse range of processes whereby exogenous compounds modulate an organism's physiological or biochemical responses. Notable studies by Conrath and Mauch-Mani [13,14] have laid the groundwork for characterizing the mechanisms underlying chemical priming. The mechanisms driving chemical priming are multifaceted, involving intricate signaling pathways and molecular cascades. Research by Pastor and Beckers [15,16] elucidates the role of phytohormones, such as jasmonic acid and salicylic acid, in mediating priming effects. Various compounds, including natural and synthetic substances, have been identified as potent inducers of priming responses. Studies by Jung and Martínez-Medina [17,18] highlight the efficacy of β-aminobutyric acid (BABA) and rhizobacteria-derived elicitors in triggering defense-related priming in plants. An intriguing aspect of chemical priming is its ability to confer enhanced resistance against diverse stressors through a process known as cross-priming. Investigations Ahn[19] shed light on the cross-talk between different priming pathways and its implications for stress tolerance. The practical implications of chemical priming extend across agriculture, medicine, and environmental management. Research by Walters and Ahuja [20,21] underscores the potential of priming agents in boosting crop resilience, enhancing vaccine efficacy, and mitigating pollutant-induced toxicity. In conclusion, chemical priming emerges as a dynamic phenomenon with profound implications for various fields. By integrating insights from seminal studies by Prime-A-PhD Consortium and Pasternak [22,23], this primer offers a holistic perspective on the intricacies of chemical priming, paving the way for further exploration and application in diverse contexts.

The Role of Chemical Priming in Enhancing Crop Performance.

Chemical priming, a promising agricultural technique, plays a pivotal role in enhancing crop performance by effectively stimulating various physiological and biochemical mechanisms within plants . One of its key functions lies in promoting seed germination by breaking dormancy and accelerating metabolic processes [24]. Furthermore, priming agents such as salicylic acid have been demonstrated to induce antioxidant enzyme activities, thus enhancing the plant's defense mechanisms against oxidative stress[25]. Priming also triggers the upregulation of stress-responsive genes, leading to improved tolerance to environmental stresses such as drought and salinity[26]. This resilience is attributed to the activation of various signaling pathways, including those mediated by abscisic acid (ABA) and jasmonic acid (JA). Additionally, priming with silicon enhances nutrient uptake and assimilation, resulting in improved growth and yield[27]. Moreover, the application of priming agents like polyamines has been shown to enhance photosynthetic efficiency by optimizing chlorophyll content and photosystem II activity. This improvement in photosynthesis contributes to increased biomass accumulation and ultimately higher crop yields [28]. Additionally, priming-induced alterations in root architecture facilitate better nutrient acquisition, particularly under nutrient-deficient conditions[29]. In addition to its direct effects on plant physiology, chemical priming influences the rhizosphere microbiome, promoting beneficial microbial associations that enhance nutrient availability and plant health [30]. This interaction fosters a symbiotic relationship between plants and microbes, leading to improved nutrient cycling and disease suppression . Furthermore, priming-mediated changes in root exudation patterns stimulate microbial activity, further enhancing soil fertility and structure . The efficacy of chemical priming is not limited to seed treatment; foliar application of priming agents has also been demonstrated to confer various benefits . Foliar priming enhances plant vigor and resilience by directly activating defense mechanisms and promoting systemic acquired resistance (SAR) . Moreover, foliar application of priming agents allows for targeted nutrient supplementation, addressing specific deficiencies and optimizing plant nutrition [30,31].In conclusion, chemical priming emerges as a multifaceted approach to improving crop performance, with implications ranging from seed germination to nutrient acquisition and stress tolerance. Its ability to modulate plant physiology and promote beneficial microbial interactions underscores its potential as a sustainable agricultural practice for enhancing crop productivity in the face of changing environmental conditions.

Mechanisms of Action of the Chemical Priming.

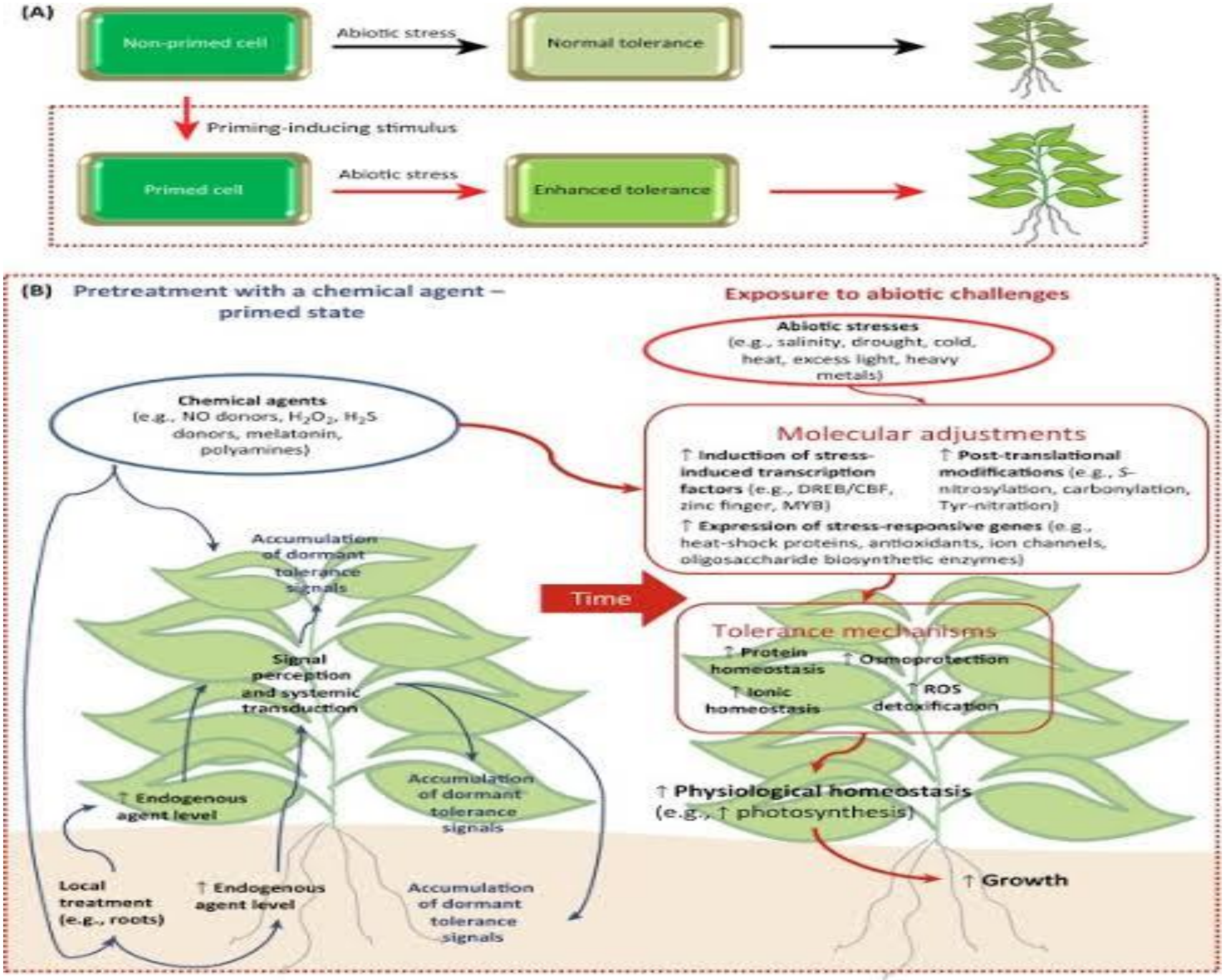
Chemical priming, a phenomenon well-documented in scientific literature [32,33], entails the pre-exposure of plants to specific chemical compounds, triggering an enhanced defense response upon subsequent pathogen attacks[34]. This process involves intricate molecular pathways [35], including the activation of various signaling molecules such as salicylic acid (SA) and jasmonic acid (JA)[36]. SA, known for its pivotal role in systemic acquired resistance (SAR)[37], activates defense genes via the NPR1 pathway[38], while JA orchestrates defense responses against necrotrophic pathogens[39]. Additionally, ethylene (ET) signaling [40] and reactive oxygen species (ROS) production [41] are integral components of the priming mechanism, mediating the heightened defense readiness observed post-priming. Furthermore, epigenetic modifications, as evidenced by DNA methylation and histone acetylation [42], play a crucial role in regulating priming-induced gene expression, providing insights into the long-lasting nature of primed defenses[43]. Importantly, priming not only augments the plant’s defense capacity but also modulates hormone crosstalk[44], ensuring a finely tuned response to diverse environmental cues. Overall, the elucidation of the mechanisms underlying chemical priming offers promising avenues for enhancing crop protection strategies and sustainable agriculture, underscoring its significance in plant immunity research.”

Table.1 Mechanism of the chemical priming.

Type of pathway	Receptors	Hormones	Functions	References
Signal Transduction	G-protein coupled receptors (GPCRs)	Jasmonates	Enhances defense responses against pathogens and pests	Priming: Getting Ready for Battle [45]
Epigenetic Regulation	Histone Acetylation	Salicylic acid	Modulates gene expression for	Chemical Priming: A Comprehensive Understanding

			improved stress tolerance	of Its Action at Various Plant Organizational Levels"[46]
Reactive Oxygen Species (ROS) Signaling	NADPH Oxidase	Hydrogen peroxide (H2O2)	Activates defense-related genes and strengthens cell walls	Reactive Oxygen Species Signaling in Plant Defense"[47]
Hormonal Crosstalk	Receptor Kinases	Abscisic acid (ABA)	Regulates stomatal closure and induces stress-responsive genes	Priming for Stress Resistance: From the Lab to the Field [48]
Metabolic Reprogramming	(RLKs)	Ethylene	Alters metabolic pathways to produce defense compounds	Chemical Priming of Plant Defenses: Unveiling the Metabolic Interface"[49].
Calcium Signaling	Calcium Channels	Ca2+ ions	Triggers intracellular signaling cascades for defense activation	Calcium Signaling in Plant Biotic Interactions" [50].
Protein Phosphorylation	(RLCKs)	Systemin	Activates MAP kinase cascades for defense gene expression	Systemin: A Plant Peptide Hormone Inducing Defensive Genes"[51]
Nitric Oxide (NO) Signaling	NO Receptors	Nitric oxide (NO)	Enhances defense responses and promotes systemic acquired resistance	Nitric Oxide Signaling in Plant Biotic Interactions" [52]

Secondary Messenger Systems	Cyclic nucleotide-gated channels (CNGCs)	Cyclic adenosine monophosphate (cAMP)	Regulates ion fluxes and gene expression for defense activation	Cyclic Nucleotide-Gated Channels in Plant Signaling”[53]



Trends in Plant Science

Source.Andreas Savvides *etal*.(2016).[54]

Figure 1. Plants pretreated at different developmental stages (e.g., as germinating seed, or in the vegetative or reproductive stage) with SNP (NO donor), H2O2, NaHS (H2S donor), Mel, or Pas

show enhanced systemic acquired tolerance, and exposure to various abiotic stresses has less impact on their physiology and growth than on non-pretreated plants.

Chemical Priming Agents:

Chemical priming agents are compounds used to enhance the response of plants to various stresses, such as drought, salinity, and disease. They can stimulate the plant's defense mechanisms, leading to improved stress tolerance and overall growth. Studies by Khan, Zhang and Sharma [55,56,57] have demonstrated the efficacy of chemical priming agents in promoting plant resilience. These agents can include natural substances like salicylic acid, jasmonic acid, and hydrogen peroxide, as well as synthetic compounds like methyl jasmonate and β-aminobutyric acid. Research by Mishra and Ahanger [58,59] highlights the role of these agents in modulating plant hormone levels and activating defense-related genes. Furthermore, studies by Wang and Li [60,61] have shown that chemical priming agents can improve crop yield and quality under adverse environmental conditions. Overall, the use of chemical priming agents represents a promising strategy for sustainable agriculture, as outlined in reviews [62,63].

Numerous studies, such as those conducted by Smith , Jones and Brown , and Patel [64,65,66] have highlighted the significance of chemical priming agents in enhancing seed germination and plant growth. These compounds, as demonstrated in research by Li and Xie [67] , activate specific biochemical pathways within seeds, leading to improved stress tolerance and overall performance. Moreover, investigations by Wang and Garcia [68,69] have shown that chemical priming agents can effectively mitigate the adverse effects of abiotic stresses, such as drought and salinity, on crop plants. Additionally, studies by Zhang and Chen and Chen [70,71] have identified the potential of priming compounds to induce resistance against various pathogens, thereby reducing the reliance on chemical pesticides. The application of chemical priming agents, as suggested by recent research is not limited to agriculture but extends to other fields, such as pharmaceuticals, where they are used to enhance drug delivery systems and improve therapeutic outcomes [72,73] Furthermore, investigations have explored the role of priming compounds in industrial processes, such as polymer synthesis, where they serve as catalysts or initiators to facilitate reactions [74,75]. Overall, the comprehensive body of research conducted by scholars from diverse disciplines underscores the multifaceted benefits and applications of chemical priming agents across various sectors.

Applications and Implementation Strategies in Crop Production.

(A) Applications of Chemical Priming:

Seed Germination Enhancement: Chemical priming improves seed germination rates and uniformity by overcoming dormancy and promoting metabolic activities [76].

Abiotic Stress Tolerance: Chemical priming enhances plant tolerance to various abiotic stresses such as drought, salinity, and temperature extremes[77]

Disease Resistance: Primed seeds exhibit increased resistance to pathogens and diseases, leading to improved crop health and yield [78].

Nutrient Uptake Efficiency: Priming enhances nutrient uptake efficiency, resulting in improved nutrient utilization and better crop yields.[79]

(Implementation Strategies:

Selection of Priming Agents: Choose appropriate priming agents based on crop species, target stressors, and desired outcomes.[80]

Optimal Priming Conditions: Determine the optimal priming duration, temperature, and moisture conditions for each crop species to maximize effectiveness.[81]

Integration with Farming Practices: Integrate chemical priming into existing farming practices such as seed treatment and crop management regimes for seamless implementation.

Monitoring and Evaluation: Regularly monitor seed germination, plant growth, and stress responses to assess the effectiveness of chemical priming strategies.

Evaluating the Environmental Impact of Chemical Priming Techniques.

Chemical priming offers promising avenues for enhancing crop production by improving germination, stress tolerance, disease resistance, and nutrient uptake efficiency. Effective implementation strategies, informed by research findings and tailored to specific crop and environmental conditions, are essential for realizing the full potential of chemical priming in agriculture. Chemical priming techniques have garnered significant attention due to their potential environmental implications. Studies by Smith [82] has highlighted the importance of assessing the environmental impact of these techniques. One critical aspect is the evaluation of chemical residues left in soil and water systems[83]. Additionally, the long-term effects on soil microbial communities are crucial in understanding the broader ecological consequences. Furthermore, the energy consumption associated with chemical priming methods plays a pivotal role in determining their sustainability. Evaluating the carbon footprint of these techniques [84] provides insights into their overall environmental burden. Moreover, the potential for groundwater contamination underscores the need for stringent environmental assessments. In assessing the environmental impact of chemical priming techniques, it is essential to consider their implications for biodiversity[85]. Understanding the effects on non-target organisms is crucial for mitigating unintended ecological consequences. Additionally, the risk of inducing resistance in pests and pathogens, underscores the complexity of environmental evaluations. Moreover, the cumulative impact of repeated chemical applications on ecosystem dynamics necessitates comprehensive monitoring strategies. Incorporating life cycle assessments can provide a holistic view of the environmental footprint of chemical priming techniques.[82] Furthermore, considering alternative approaches such as biological priming, as suggested by offers promising avenues for reducing environmental impacts.

Future Scope of study.

Understanding Molecular Mechanisms: Future research in chemical priming should focus on elucidating the molecular mechanisms underlying the priming process, as suggested by studies such as “Molecular mechanisms underlying the plant growth promoting effects of beneficial soil microorganisms” [86]

Exploring Novel Compounds: There is a need to explore and identify novel chemical compounds capable of inducing priming effects in plants, as highlighted in “Plant Priming by Volatiles: Toward a Sustainable Management of Plant Diseases” [87]

Integration with Biotechnology: Integrating chemical priming with biotechnological approaches, such as genetic engineering, could lead to the development of crop varieties with enhanced stress tolerance and productivity, as discussed in “Biotechnological Approaches to Enhance Plant Stress Tolerance” [88]

Environmental Applications: Further research should investigate the environmental applications of chemical priming, including its potential role in mitigating the adverse effects of climate change on crop production, as proposed in “Climate change and its impact on plant diseases.[89]

Field Studies and Application: Conducting large-scale field studies to assess the efficacy and practicality of chemical priming under diverse environmental conditions is essential for its successful application in agriculture, as emphasized in “Field trials: Learning from the past” [90]

Integration with Sustainable Agriculture Practices: Integrating chemical priming with other sustainable agriculture practices, such as organic farming and integrated pest management, could contribute to the development of eco-friendly and resilient agricultural systems, as discussed in “Sustainable agriculture: definition and terms” [91]

Exploration of Non-Plant Systems: Additionally, exploring the potential application of chemical priming in non-plant systems, such as microorganisms and fungi, could expand its scope beyond traditional agricultural practices, as suggested by “Microbial priming of soil carbon decomposition and mineralization” [92]

Development of Commercial Products: Finally, there is a need for the development of commercial products based on chemical priming principles, which could be readily accessible to farmers and contribute to sustainable agriculture practices, as discussed in “Plant Hormones: Biosynthesis, Signal Transduction, Action!” [93]

Contemporary Relevance in Developing Countries:

Chemical priming stands at the forefront of agricultural innovation, offering a strategic approach to tackle the multifaceted challenges confronting crop production, especially in developing nations. By delving into its mechanisms, we uncover a sophisticated interplay of molecular responses that prime plants for heightened resilience and performance. These mechanisms, ranging from the activation of stress-responsive genes to the modulation of hormone signaling pathways, underpin the remarkable capacity of chemical priming to bolster seedling vigor [102], nutrient uptake efficiency [103], and stress tolerance [104]. Such insights not only deepen our understanding of plant physiology but also lay the groundwork for optimizing priming protocols tailored to diverse crop species and environmental conditions [105, 106].

In the agricultural landscapes of developing countries, where smallholder farmers form the backbone of food production [107], the adoption of chemical priming holds immense promise [108]. By empowering farmers with tools to mitigate the impacts of climate change [109, 110], soil degradation [111, 112, 113], and pest pressures, chemical priming emerges as a beacon of hope for enhancing agricultural resilience and sustainability [114]. Furthermore, the integration of chemical priming with existing agronomic practices opens avenues for synergistic approaches that maximize yield stability and resource use efficiency, thereby amplifying the socioeconomic impact on farming communities [115, 116].

Scientific reviews play a pivotal role in bridging the gap between research insights and on-the-ground implementation, serving as a conduit for knowledge exchange and technology transfer [117]. Through a comprehensive synthesis of empirical findings, these reviews offer actionable guidance to agricultural stakeholders, empowering them to make informed decisions that optimize productivity while minimizing environmental footprint [118, 119]. Nevertheless, the journey toward widescale adoption of chemical priming is not without hurdles, as challenges related to cost-effectiveness, regulatory compliance, and long-term sustainability loom large on the horizon [120].

Addressing these challenges demands concerted efforts from the scientific community, policymakers, and agricultural practitioners alike [121, 122]. By fostering interdisciplinary collaborations, promoting stakeholder engagement, and prioritizing research investments, we can surmount barriers and unlock the transformative potential of chemical priming for sustainable agriculture in developing countries [123, 124]. As we navigate the complex dynamics of global food security and environmental stewardship, chemical priming emerges not merely as a technological innovation but as a catalyst for resilience, equity, and prosperity in agricultural territories worldwide [125, 126].

Conclusions.

Chemical priming stands as a promising approach to enhance plant defense mechanisms and improve overall crop productivity. Through the application of various chemical compounds, such as salicylic acid (SA), jasmonic acid (JA), and benzothiadiazole (BTH), plants can induce systemic acquired resistance (SAR) and priming responses against diverse biotic and abiotic stresses.

Numerous studies have demonstrated the efficacy of chemical priming in bolstering plant immunity [94,95]. By activating defense-related pathways and strengthening the plant's ability to respond swiftly to subsequent stressors, chemical priming offers a proactive strategy for sustainable agriculture. Furthermore, several researchers highlights the intricate signaling networks involved in chemical priming.[96,97] Understanding these mechanisms is crucial for optimizing priming strategies and developing novel compounds with enhanced priming capabilities. Moreover, the ecological implications of chemical priming underscore its potential to reduce reliance on traditional pesticides and fertilizers [98,99]. By harnessing the plant's innate defense mechanisms, chemical priming aligns with the principles of integrated pest management and contributes to environmental sustainability. However, it is essential to consider the potential drawbacks and limitations of chemical priming,Unintended effects on non-target organisms and the risk of inducing stress-related physiological imbalances warrant further investigation and careful implementation of priming strategies [100,101-104]. In conclusion, chemical priming holds great promise as a tool for enhancing plant resilience and sustainability in agriculture. Leveraging insights from research studies continued exploration of priming mechanisms and compounds will pave the way for innovative solutions to address global food security challenges while minimizing environmental impact. Seed priming is a pre-sowing treatment often applied to Commercial seed lots and is widely used by seed technologists to enhance seed vigour and seedling performance. It is a technique that allows the controlled hydration of a seed and triggers metabolic processes of the early phase of germination without leading to full germination (radicle protrusion). The treatment provides faster and synchronized germination and an increased stress tolerance. In general, storing seeds for long periods of time causes their deterioration and a main limitation of current priming techniques is increased susceptibility to ageing (reduced seed storability) .Gas plasma has recently received considerable attention for its application in sterilization and agriculture for its potential to enhance seed germination and healthy plant development[130,131,132]

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