PLANT SCIENCE TODAY
Vol 12(sp3): 01–08
https://doi.org/10.14719/pst.8436

eISSN 2348-1900

REVIEW ARTICLE

Insights into pre-harvest sprouting dynamics in groundnut

R Ezhilarasi[1*], T Ragavan[1], E Subramanian[2], R Amutha[3], A Mothilal[4] & Sangeetha Jebalin V V[1]

[1]Department of Agronomy, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India
[2]ICAR-Krishi Vigyan Kendra Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India
[3]Department of Crop Physiology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India
[4]ICAR-Krishi Vigyan Kendra, Virudhachalam 606 001, Tamil Nadu, India

*Correspondence email - ezhil4816@gmail.com

Received: 17 March 2025; Accepted: 11 November 2025; Available online: Version 1.0: 10 December 2025

Cite this article: Ezhilarasi R, Ragavan T, Subramanian E, Amutha R, Mothilal A, Sangeetha JVV. Insights into pre-harvest sprouting dynamics in groundnut. Plant Science Today. 2025;12(sp3):01–08. https://doi.org/10.14719/pst.8436

Abstract

The cultivation of groundnut is essential for sustaining economic activity, improving soil fertility, oil content and promoting food security. Because of its flexibility and adaptability, it is an essential crop for both commercial and subsistence farming. Pre-harvest sprouting of groundnut (*Arachis hypogaea* L.) seeds poses a significant challenge due to their non-dormant nature. Spanish and Valencia bunch cultivars pose significant agricultural difficulty because of uncontrolled sprouting due to rainfall or high soil moisture during harvest. Field sprouting in bunch varieties results in a 20 %-25 % yield decrease. Kernels also grow when they are piled on the threshing floor with high moisture content. In dormant bunch cultivars, yield losses from viviparous germination can be reduced for a short period of time (3-4 weeks) because of their natural dormant character. To prevent pod losses from rainfall during harvest, seeds should be induced into dormancy for at least three weeks. Seed dormancy induction in standing crops can be accomplished through foliar application of targeted chemical treatments, which has been shown to be an effective approach. Apart from that, a few semi-spreading and spreading species (Virginia type) show variable lengths of dormancy compared to bunch cultivars. Genetic modification of these cultivars to introduce seed dormancy is the most practical way to solve this problem. To successfully incorporate seed dormancy into Spanish and Valencia bunch types, one must have a thorough understanding of the inheritance patterns of this feature and how it interacts with other plant and pod/kernel traits.

Keywords: bunch type; dormancy; groundnut; growth inhibitor; pre-harvest sprouting

Introduction

Groundnut (*Arachis hypogaea* L.) is a member of the Leguminosae family. Because of their ideal agro-climatic conditions for groundnut growing, Asia and Africa account for about 95 % of the world's planted land and 87 % of its production (1). Groundnut meal provides approximately 53 % nutritional digestibility and 88 % crude protein digestibility when fed to cattle. Haulms have an energy release of up to 2337 calories per kilogram of dry materials. As a leguminous crop, groundnut enhances soil fertility and overall soil health through biological nitrogen fixation and the incorporation of organic residues (2). Haulms of groundnuts are a healthy way to feed livestock. Compared to cereal fodder, they contain higher amounts of protein (8 %-15 %), lipids (1 %-3 %), minerals (9 %-17 %) and carbohydrates (38 %-45 %) (3).

Globally, groundnut is cultivated under 295 lakh hectares with the production and productivity of 487 lakh tonnes and 1647 kg ha^{-1}. India is among the top three groundnut-producing countries in the world (4). Groundnut is a major oilseed crop in India, ranking first in area and second in production after soybean. With 18.36 million tonnes of production, China leads the world in groundnut production, followed by India with 10.24 million tonnes Fig. 1. India contributes over 15 % of the world's groundnut crop (5). Groundnut is mainly grown during the *Kharif* season in India. It is also grown as an irrigated crop in several states throughout the *rabi* and summer seasons, but nearly 80 % of the area and production occurs during the *kharif* season (June-October).

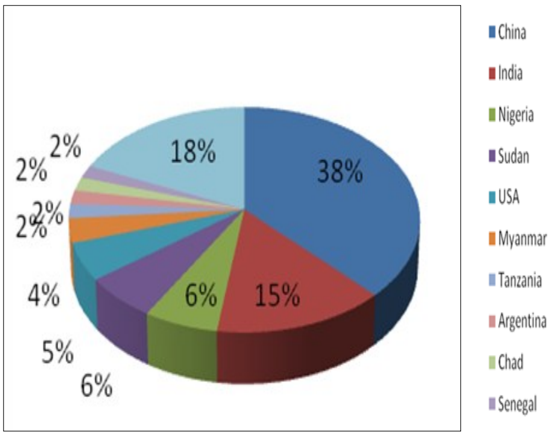

Fig. 1. India's position in the production of groundnuts (with shells) in the World.

Currently, six major states-Gujarat, Andhra Pradesh, Rajasthan, Karnataka, Tamil Nadu and Maharashtra-account for about 80 % of India's groundnut cultivation area. The remaining 20 % is concentrated in Madhya Pradesh, Telangana, Uttar Pradesh and West Bengal (6). In Tamil Nadu, groundnut is cultivated on 0.409 million ha, producing 1.023 million tonnes annually with a productivity of 2.50 tonnes ha^{-1} (7).

A significant oilseed crop, groundnuts will account for about 37 % of the nation's oilseed production (8). Groundnut oil is a heart-healthy choice due to its high vitamin E and powerful antioxidant content. Additionally, this oil contains monounsaturated and polyunsaturated fats, collectively referred to as unsaturated "good" fats. This unsaturated fat highlights a notable decrease in the risk of heart disease (9). Indian exporters export groundnut oil to 1736 buyers worldwide (10). Additionally, the export has increased gradually from 2019 to 2022 (Table 1) (5). India is the third-largest exporter of groundnut oil worldwide, with the majority of its exports going to China, Singapore and the United States.

Table 1. Quantity and value of exports of Groundnut oil meal and vegetable oil from India

Years	Vegetable Oil (tonnes)	Oil meal (tonnes)
2019-20	12171.24	7558
2020-21	17057.29	8803
2021-22	18627.16	9877

There are two subspecies of the cultivated groundnut, *Arachis hypogaea* L. - *hypogaea* subspecies (The Virginia bunch and Virginia bunch variants) and the *fastigiata* subspecies (Spanish and Valencia types) (11). Subspecies *fastigiata*, which includes the Spanish and Valencia market types, accounts for 60 % of the world's groundnut production area. However, the kernel of groundnut is not dormant in the case of subspecies, which principally creates the primary problem of *in-situ* germination. Because of groundnut's natural underground fruit bearing character, they require enough moisture in the soil to be harvested. Rain during the harvest season causes seeds to sprout in the field itself. Therefore, seed dormancy is considered a crucial trait in groundnut to minimize yield loss (12).

Although dormancy is a natural evolutionary consequence in groundnut, it can be advantageous or detrimental depending on the circumstances. Bunch types in groundnuts are typically non-dormant. They are therefore more susceptible to *in-situ* germination (13). Later conditions cause the bunch varieties to lose a significant number of seeds due to sprouting. While the partially sprouted seed is low-quality, low-oil content and tends to deteriorate quickly, the fully germinated seed is pretty useless. Due to *in situ* germination, bunch groundnut pod yields have been reported to have decreased by 20 %-40 % (14). Heavy rains caused 80 % of groundnut seeds to germinate in the field, especially rain at pod maturity phase, causing 20 %-50 % of pods to germinate (15).

Thus, the main issue with bunch groundnut cultivation is thought to be the seed's non-dormant nature. To overcome such situations, it is essential to develop strategies to induce seed dormancy in the major bunch-type groundnut-growing regions to prevent field sprouting.

Relationship between bunch type and field sprouting

In cultivated groundnut (*Arachis hypogaea* L.), there are two subspecies according to Kalra and Srivastava (Fig. 2). According to them, in the last twenty years (from 2001 to 2021), 117 different groundnut cultivars has been introduced in India; the majority of these are 76 Spanish bunch cultivars, with the remaining cultivars being 29 Virginia bunch and 12 Virginia runner.

Spanish bunch cultivars are therefore more common in Indian conditions because they work well with groundnut cropping systems and all three seasons. The foundational elements of Valencia and Spanish bunch types are typically not dormant, in contrast to the Virginia varieties (16).

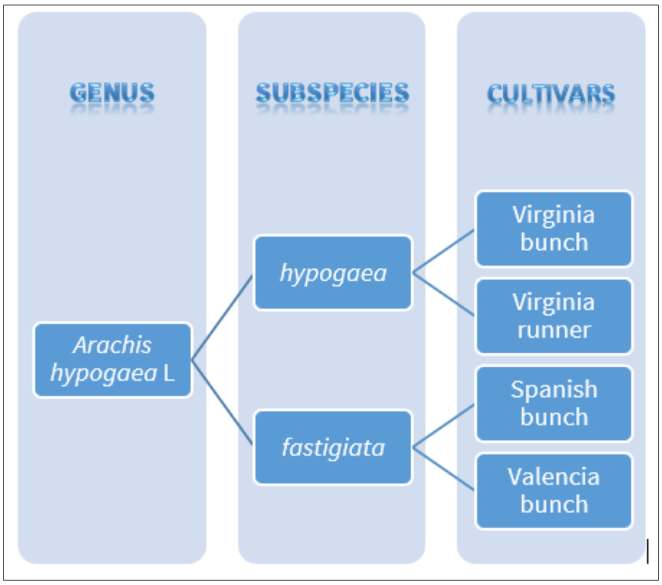

Fig. 2. Different groundnut (*Arachis hypogaea* L.) cultivars.

When it comes to pre-harvest sprouting, bunch-type groundnuts are more likely than other types to experience it (17). This can be explained by several factors related to their developmental habits, structures and environmental circumstances. Pre-harvest sprouting is more common in bunch-type groundnuts due to their pod structure. In bunch kind, pods grow generally in clusters (18). Because of the close spacing between the pods, a microenvironment with higher humidity and less air circulation may be produced. Pre-harvest sprouting may occur more readily under such conditions, particularly if the crop is exposed to high humidity or prolonged rainstorms.

In the final phases of pod growth, rain or excessive humidity can occur more easily and in bunch-type groundnuts, they may have limited air circulation because of the thick pod arrangement, which can hinder the crop's ability to dry completely (19). Avoiding sprouting requires careful drying and bunch-type groundnuts may retain more moisture due to poor air circulation (20). A crop's ability to withstand early germination can be influenced by a variety of varietal traits, including seed coat permeability and dormancy (21). A bunch variety may be more likely to mature later in the growing season. Pre-harvest sprouting is more likely to occur if harvesting is postponed and the crop is left in the field during wet or humid spells (22).

Farmers frequently need to implement cautious harvesting techniques, give prompt harvesting top priority and ensure the right post-harvest drying conditions to control pre-harvest sprouting in bunch-type groundnuts. To further reduce the effect of this phenomenon on crop output and quality, choose cultivars that are more resistant to sprouting, pay attention to weather forecasts and pay attention to the attention to be paid.

Factors influencing pre-harvest sprouting

Pre-harvest sprouting (PHS) is a noteworthy stress-inducing characteristic in groundnuts. PHS is an environmental phenomenon that appears when rainy, humid weather occurs around the time of seed maturity (23). This climate alignment causes bunch-type groundnuts to germinate prematurely. This is especially noticeable in areas with strong soil moisture retention, such as black soil areas and results in higher rates of pod sprouting (24). Prolonged rainy spells or high humidity can foster a favourable environment for sprouting. The germination process may be initiated by the pods' absorption of moisture (25). Maturity Level of the kernels is a crop factor that causes severe germination in the field itself. When mature groundnuts are left in the field for a long time, they may sprout before harvest. This is especially true for bunch-type groundnuts (26). Postponing harvesting might expose the crop to adverse weather conditions, thereby increasing the risk of sprouting.

In addition to external variables, numerous internal components are essential for pre-harvest germination in groundnuts. It has been determined that carbohydrate metabolites, plant hormones, nitric oxide (NO), reactive oxygen species (ROS) and microRNAs (miRNAs) have a significant role in the regulation of PHS (27). Two important phytohormones, gibberellin (GA) and abscisic acid (ABA), are necessary for coordinating the internal signalling networks associated with PHS (28). Phytohormones play a crucial role as endogenous regulators in plants at different phases of their growth and development. Over the past few decades, ABA (29), GA and several other plant hormones, such as auxin/indole-3-acetic acid (IAA), jasmonate (JA), ethylene (ET) and brassinosteroid (BR) (30) have been linked to the complex control of PHS.

Genetic studies have revealed that indispensable genes in cellular responses, such as mitogen-activated protein kinase kinase 3 (MKK3), are causal for PHS (31). Pre-harvest germination is primarily caused by an imbalance in the dormancy/germination ratio. Wild ancestors often exhibit strong seed dormancy in their natural habitats, which helps delay germination under unfavourable conditions (32). As such, compared with their wild counterparts, domesticated crop species have reduced degrees of dormancy (33).

Minimizing *in-situ* sprouting and optimizing groundnut production are primarily dependent on controlling the amount of water available during the various growth stages. The yield increased significantly by 41 % as a result of this strategic water management (34). It has been observed that pod yields of bunch groundnut are significantly reduced by 20 % when germination occurs *in-situ* (35). Heavy rainfall has been linked to a high incidence of groundnut seed germination up to 80% in the field and 20 %-50 % of pods have been shown to germinate when rain falls during the pod maturity stage (36).

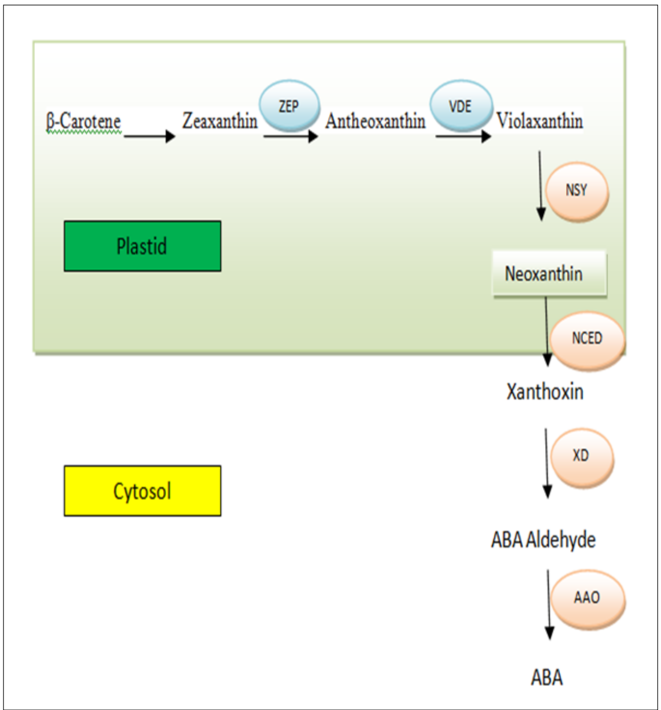

Fig. 3. ABA synthesis in plants.

Pre-harvest sprouting's effect on yield and quality

In groundnuts, *in-situ* sprouting has a significant effect on the crop's quality in addition to quantity. According to observations in the Pati district of Central Java, the oil content of peanut seeds varies with season: 42 %-50 % during the wet season and 40 %-48 % during the dry season (37). In a similar vein, sprouting seeds in the Banjar Negara district of Central Java had much less oil between 20 % and 29 % (38). The impact of pre-harvest sprouting (PHS) extends beyond groundnuts. It is a well-documented issue in various cereal crops, including maize, wheat, rice, barley and sorghum, found in regions such as North Africa, Europe, China, Japan, the United States, Canada and Australia (39). PHS is recognized as a global issue, occurring in major regions of the world every ten years. Food security and agricultural productivity are at risk because of PHS's loss in grain production and end-use quality (40). To reduce the yield losses because of PHS, dormancy of the seeds should be induced through chemical sprays or genetic modification of non-dormant to dormant seeds.

Hormonal and genetic engineering for switching off sprouting

In the realm of natural processes, some wild species, such as the hardy mangroves, benefit ecologically from vivipary germination, in which seeds sprout while still attached to the parent plant. But when it comes to farmed crops, early seed germination, such as pre-harvest sprouting, poses a threat to global food security. PHS negatively affects kernel quality, resulting in substantial financial losses for growers (41). Seed hormone biology is a promising way to mitigate the harmful impacts of PHS. Interestingly, abscisic acid (ABA) turns out to be a key hormone controlling dormancy in seeds (42). With skilful manipulation of ABA production (Fig. 3), dormancy can be increased and early germination can be prevented. Modulating the expression of nine-cis-epoxy carotenoid dioxygenase (NCED), an enzyme that limits ABA production, is an effective tactic. This modification is accomplished through an advanced chemically driven gene expression method, proving its effectiveness in preventing the germination of fully grown seeds (43).

Additionally, an EPA-approved chemical has been used to demonstrate the feasibility of the NCED-inducible system (44). This method is a calculated attempt to reduce pre-harvest sprouting (PHS) by adjusting the amount of abscisic acid (ABA) in seeds. Extensive testing of PGSS-induced NCED expression in *Arabidopsis* has yielded promising results (45). Among the tested approaches, only NCED induction showed strong potential for effectively suppressing seed germination (46). Additionally, this inducible approach showed promise in suppressing early germination of seeds when they are attached to the plants, which is seen in cereals (47).

A clear difference can be seen in the complex patterns of nature between the seed dynamics of wild species, marked by strong seed dormancy and those of agricultural crops we grow, which typically show little to no dormancy at all. The domestication process is responsible for this divergence in dormancy features, as our cultivated crops' wild predecessors once possessed these crucial dormancy mechanisms (48).

Genetic research has greatly expanded our knowledge of pre -harvest sprouting (PHS) resistance and seed dormancy by delving into the complex field of genetics. Through these investigations, a remarkable mosaic of genes that are closely linked to germination and dormancy is independently attributed (49). The investigation of genes essential to cellular responses has shown mitogen-activated protein kinase kinase 3 (MKK3) as a key mediator in the development of PHS, which is intriguing (50). This gene has been identified as a direct contributor to seed susceptibility or resistance to early germination. A multitude of genes with diverse biochemical functions have been associated with either conferring resistance or increasing susceptibility to PHS, further complicating the trait (51). Interestingly, a sizable portion of these genes is closely related to hormone signalling, including the complex dance of abscisic acid (ABA) signalling (Fig. 4) (52). The complexity of the regulatory networks controlling seed dormancy and germination is highlighted by the inclusion of MKK3 in this genetic orchestra, which may indicate downstream links or involvement in ABA signal transduction (53).

In the complex network of regulatory mechanisms coordinating pre-harvest sprouting (PHS), abscisic acid (ABA) is a key component. The key to avoiding PHS often lies in maintaining high grain ABA content; ABA-mediated systems regulate this delicate balance (54). The expression of ABA response genes is subsequently influenced by these transcriptional maestros, deftly arranging the molecular ballet that governs PHS.

The careful regulation of ABA levels in the grains is the primary mechanism by which ABA demonstrates its regulatory power over PHS. The synthesis and degradation of ABA are closely related to this control. First, geranyl-geranyl pyrophosphate (GGPP) is converted. This compound is a precursor closely associated with the onset of β-carotenoid biosynthesis, which in turn serves as a precursor for ABA (55).

Through meticulous plant breeding, the crossing of dormant and non-dormant parents, has yielded insightful results. These crossings produced F_1 progenies that were dormant and the predictions in the F_2 generation were based on this observed shift, with a ratio of 3 dormant to 1 non-dormant progenies supporting the trait's heritability (56). Additional understanding has been gained regarding the genetic mechanisms underlying fresh seed dormancy (57). The aim is to incorporate the fresh seed dormancy trait into the genetic makeup of modified lines.

In a follow-up study, this dormant trait was deliberately introduced into the genetic makeup of two groundnut cultivars, Shitaochi and Aprewa, which are usually non-dormant (58). The selected exotic lines, ICGV 87378 and ICGV 86158, are particularly well-known for having the desirable dormancy characteristic in fresh seeds. Based on the genetic foundation, their investigation bolsters the notion that seed dormancy is controlled by monogenic inheritance (59). Notably, the study confirms that in the observed inheritance patterns, dormancy prevails over non-dormant situations. The F_1 progenies were always latent, regardless of the gender of the dormant parent. This discovery casts doubt on the idea that the mother controls groundnut dormancy, suggesting that the genetic basis of dormancy is independent of the maternal parent (60). Furthermore, the results are consistent with previous findings indicating a common locus for the dormant gene, suggesting that seed dormancy in both parents is controlled by the same genetic locus (61). Dormant parents' backcross progenies conformed to the predicted 1:1 ratio of dormant to non-dormant, confirming the heritability of dormancy (62).

The Germination Stability Index (GSI) was used to carefully evaluate the stability and fresh seed dormancy of different groundnut genotypes (63). The results showed that PBS 12192, PBS 12187, PBS 12191 and PBS 12190 were the top breeding lines, with extremely low GSI values. This finding confirms their position as the genotypes with the highest degree of stability in the study, along with their excellent ability to maintain high fresh seed dormancy.

Dormancy induction through chemicals

Abscisic acid (ABA)

Groundnut seed dormancy has been thoroughly studied, highlighting the critical role of embryonic ethylene production in the germination process (64). Their results demonstrated that, by blocking ethylene synthesis, topically applied abscisic acid (ABA) is essential for preserving seed dormancy. Building on this knowledge, a meaningful connection has been established between ABA and the imposition and maintenance of seed dormancy (65). This study, which primarily examined cereals such as barley, wheat and sorghum, highlighted the regulatory role ABA plays in the development of primary dormancy. The expression of dormancy during grain imbibition is closely linked to the preservation of elevated ABA levels. On the other hand, ABA content significantly decreases in embryos of dormant and non-dormant grains exposed to germination-promoting circumstances (66). In contrast, it has been discovered that treating oat seeds with fluridone inhibits the induction of thermo-dormancy, suggesting that ABA synthesis plays a role in this phenomenon (67). It has also been demonstrated that secondary dormancy can be effectively induced under conditions that facilitate ABA production (68). Furthermore, because ABA builds up in dormant nodes and increases when the tissue is exposed to low temperatures, it has been proposed that ABA induces

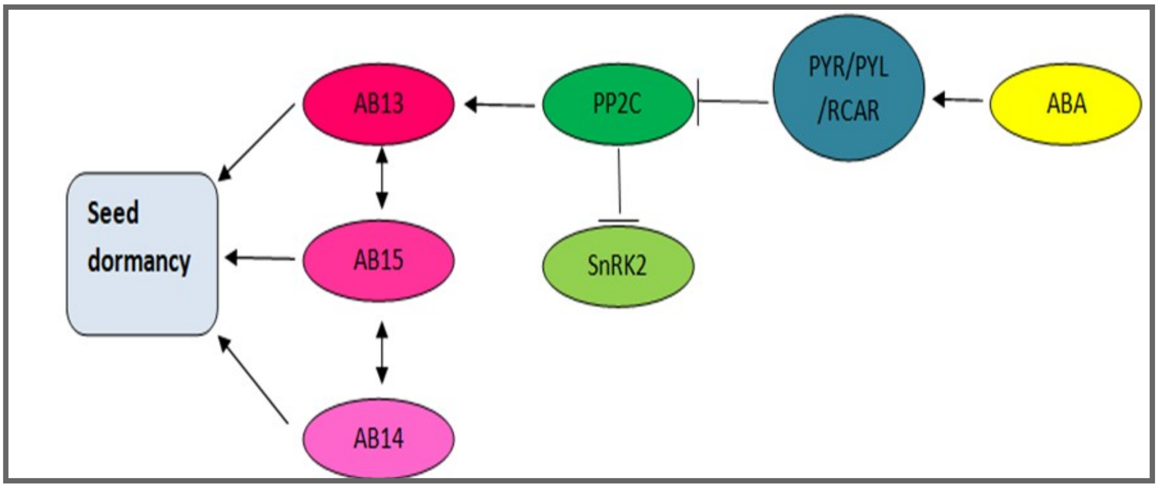

Fig. 4. ABA signalling in dormancy induction.

dormancy.

Different growth retardants were evaluated for their effect on inducing dormancy in the non-dormant groundnut cultivar TMV 7. The results clearly demonstrated that ABA at 500 ppm, used 70 days after sowing, was the most effective in inducing dormancy in the resulting seeds (24). The non-dormant bunch-type groundnut cultivar KCG 2 has undergone dormancy induction, achieved by applying 150 ppm abscisic acid topically at pod maturity (69). The dormancy extension that this application produced, up to 16 days, has also been concluded to highlight the function of abscisic acid in controlling seed dormancy.

Maleic Hydrazide (MH)

Several growth inhibitors are essential for inducing groundnut dormancy, including ABA, Maleic Hydrazide and γ-radiation treatments (70). It has been possible to effectively induce fresh seed dormancy in Spanish bunch cultivars by applying maleic hydrazide topically at 1000 and 1250 ppm. This therapy successfully induces dormancy in the seeds when treated 60 and 90 days after sowing, demonstrating the effectiveness of Maleic Hydrazide as a dormancy-inducing agent (69).

The concentration of Maleic Hydrazide is closely correlated with reaching a higher degree of dormancy (71). Dormancy was successfully induced in two types of bunch groundnuts, Spanish enhanced and TMV2, by foliar spraying 500 ppm MH 15 and 25 days before harvest. The number of sprouts dropped from 13.3 to 1.8 in the case of Spanish enhanced groundnuts and from 17.5 to 5.8 in the case of TMV-2 (72). In another study, maleic hydrazide-30 was applied as a foliar spray at concentrations of 0, 5000, 10000, 15000, 20000, 25000 and 30000 ppm at 70, 80 and 90 DAS. The results indicated that all treatments, regardless of the application stage, significantly reduced germination of non-dormant seeds while increasing the overall level of free amino acids, thereby contributing to the induction of dormancy (73). Concentrations ranging from 250 to 1000 PPM, increasing dormancy by 60 %-80 % (74). Applying MH at lower concentrations (250 ppm) at the earliest stage of crop growth (60 days) was just as effective at inducing seed dormancy as higher concentrations (75). In Gupta's field trial, to induce dormancy, foliar treatments of MH at concentrations of 5 x 1000, 10 x 1000 and 15 x 1000 ppm were applied at 70 and 90 days after sowing in a groundnut variety T64. The study of yield and yield components showed that spraying chemicals at concentrations of 15 × 1000 and 20 x 1000 ppm at 90 days after sowing increased the degree of dormancy induction (76).

Mishra proposed that applying MH topically at 1000 ppm 60 days after crop emergence was the most efficient way to induce dormancy in groundnuts (77). Bunch-type groundnut genotypes were able to induce dormancy with foliar spraying of 250 ppm of MH sprayed 60 days after sowing (DAS) (78). On the other hand, there is little and conflicting data on how MH affects groundnut seed dormancy. Maleic Hydrazide has herbicidal and growth-inhibiting properties (79). In this investigation, three distinct groundnut cultivars, TG 38 B, Devi and TG 37 A received foliar spray treatments containing six different doses of MH at intervals of 70 and 90 DAS. The findings showed that all three kinds of MH treatments caused partial seed dormancy that lasted for up to a week at lower concentrations. Application of MH foliar spray at 60 days after planting induced greater seed dormancy than later applications, with 250 ppm-1,000 ppm achieving 60 %-80 % dormancy (80).

Cycocel (CCC)

CCC (Cycocel) inhibits the germination of groundnut seeds and acts as a synthetic growth retardant (81). The decrease in diffusible auxin from pea plants in the presence of CCC is thought to be the cause of this inhibitory activity. CCC reduces the germination of groundnut seeds (82). Additionally, it has been observed that CCC inhibits the synthesis of substances that resemble gibberellic acid (GA) in non-dormant wild oat, wheat and barley embryos. The current study confirms previous findings that Maleic Hydrazide (MH) induces dormancy in groundnut seeds (83).

Other chemicals

The role of salicylic acid in inhibiting the growth of various plants and inducing seed dormancy has been explored in several studies. For the dormant groundnut variety TMV-3, Sreeramulu examined the seeds at various storage times (0, 10, 20, 30 and 40 days after harvest). It was shown that the end of dormancy occurred 30 days following storage because of the drop of synergistic phenolic acid in the cotyledons and embryonic axis (84). Similarly, the inhibition of germination in small seeds could be explained by the presence of endogenous inhibitors, such as salicylic acid, syringic acid and chlorogenic acid (85). It was discovered that exogenous administration of these highly potent phenols at 10^{-2} M prevented germination. Furthermore, the effect of salicylic acid on the development of defensive mechanisms (86). He discovered that salicylic acid inhibits the germination of Arabidopsis seeds and boosts their tolerance to water stress. *Coctus speciosus* rhizome dormancy has been linked to coumaric acid, cinnamic acid and trace levels of salicylic acid (87).

Conclusion

Groundnut (*Arachis hypogaea* L.) is now considered an essential crop for food security and economic growth. This adaptable crop produces products such as cake and oil, which are widely used in both industrial and domestic settings. Groundnuts are becoming more important, but they pose a serious threat from *in-situ* sprouting when pod harvesting is delayed past physiological maturity or occurs during precipitation. Farmers who greatly depend on the revenue from groundnut production face a serious threat to their livelihoods as a result of this premature sprouting, which drastically reduces pod yields. To protect farmers' economic interests and maximize groundnut pod yields, a diversified strategy is essential. It is imperative to motivate farmers to adopt enhanced groundnut cultivars suited to their unique agro-climatic circumstances. Growth retardant chemicals play a crucial role in controlling the *in-situ* sprouting of kernels, ensuring better seed quality, extended shelf life and reduced economic losses. They help farmers to improve yield, quality and marketability while preventing post-harvest losses and seed degradation. Additionally, a crucial component is emphasizing the need to harvest at physiological maturity and to refrain from irrigation during this crucial time. By combining these strategies, we can strengthen the economic stability of groundnut producers while simultaneously ensuring maximum yields.

Acknowledgements

I want to express my heartfelt sense of gratitude to the members of Advisory Committee for laying out the guidelines of research work and framing my mind to think logically and systematically in order to carry out my research work properly. Funding of the study was provided by Venture Capital Scheme of Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India.

Authors' contributions

RE contributed to the collection of literature, data collection, data interpretation and writing of the article. TR provided guidance throughout the writing process and ES also guided the preparation of the article. RA offered guidance in writing and assisted with necessary corrections, while AM supported the article preparation through guidance. SJW assisted with alignments and provided economic support. All authors read and approved the final manuscript before publishing.

Compliance with ethical standards

Conflict of interest: The authors have declared that no competing interests exist.

Ethical issues: None

References

1. Poonia T, Kumawat S, Kumar S. Influence of tillage and nutrient management practices on peanut yields, economic and resource efficiency in the Thar Desert of South Asia. J Agric Sci Technol. 2022;22(4):785-97. https://doi.org/10.21203/rs.3.rs-1381293/v1
2. Peoples MB, Giller KE, Jensen ES, Herridge DF. Quantifying country-to-global scale nitrogen fixation for grain legumes: I. Reliance on nitrogen fixation of soybean, groundnut and pulses. Plant Soil. 2021;1-14. https://doi.org/10.1007/s11104-024-07033-7
3. Akshaya A, Kumarimanimuthuveeral D, Kumar KS. Integrated nutrient management practices on the physiological and yield traits of irrigated groundnut (*Arachis hypogaea* L.). Pharma Innov J. 2022;11(9):140-2. https://www.thepharmajournal.com/archives/2022/vol11issue9/PartX/11-8-506-289/IC
4. FAOSTAT. 2023. https://www.fao.org/faostat/en
5. Indiastat. 2023. https://www.indiastat.com
6. Krithika KM, Maheswari N, Sivagami M. Models for feature selection efficient crop yield prediction in the groundnut production. Res Agric Eng. 2022;68(3):131-41. https://doi.org/10.17221/15/2021-RAE
7. Suthar B, Pundir RS, Gundaniya H, Mishra K. Growth and instability analysis of area, production and yield of groundnut in selected states of India. Environ Conserv J. 2024;25(1):192-8. https://doi.org/10.36953/ECJ.24692665
8. Thirumeninathan S, Pazhanivelan S, Sudarmanian N, Ragunath K, Gurusamy A, Sritharan N. Rabi groundnut area estimation using synthetic aperture radar (SAR) in Thiruvannamalai district of Tamil Nadu. Legume Res Int J. 2022;45(3):319-26. https://doi.org/10.18805/LR-4746
9. Dwivedi SL, Nigam SN, Rao RN, Singh U, Rao KVS. Effect of drought on oil, fatty acids and protein contents of groundnut (*Arachis hypogaea* L.) seeds. Field Crops Res. 1996;48(2-3):125-33. https://doi.org/10.1016/S0378-4290(96)01027-1.
10. Dey A, Gautam Y. An assessment of export competitiveness of Indian groundnut. Indian J Agric Mark. 2023;37(1):1-9.
11. Kalra L, Srivastava S. Analysis of growth in area, production and productivity of groundnut in major producing states of India. Pharma Innov J. 2022;11(4):771-7. https://www.thepharmajournal.com/archives/2022/vol11issue4S/PartK/S-11-4-17-917
12. Nautiyal PC, Sivasubramaniam K, Dadlani M. Seed dormancy and regulation of germination. Seed Sci Technol. 2023;39-66. https://doi.org/10.1007/978-981-19-5888-5_3
13. Shobha K, Renugadevi J, Jerlin R. Studies on seed dormancy and breaking methods in groundnut cv. VRI 7. 2020. https://doi.org/10.29321/MAJ.2020.000357
14. Nautiyal P. Issues related to maintenance of seed viability and regulation of dormancy in groundnut. Groundnut Res India. 2004;321-38.
15. Kombiok J, Buah S, Dzomeku L, Abdulai H. Sources of pod yield losses in groundnut in the Northern Savanna zone of Ghana. West Afr J Appl Ecol. 2012;20(2):53-63. https://doi.org/10.4314/wajae.v20i2
16. Rani MS, Rao P, Durga KK, Bharathi V, Bharathi K, Reddy AV. Induction of dormancy in non-dormant varieties of groundnut. J Cereals. 2013;4(7):89-93. https://doi.org/10.5897/JCO2013.0116
17. Zongo O, Abdou R, Salamatou SA, Kouassi AST, Yacoubou B. Agro-morphological variability in eight Bambara groundnut (*Vigna subterranea* (L.) Verdc.) morphotypes from Zinder (Niger). Agric Sci. 2023;14(1):1-10. https://doi.org/10.4236/as.2023.141001
18. Unigwe AE, Gerrano AS, Adebola P, Pillay M. Morphological variation in selected accessions of Bambara groundnut (*Vigna subterranea* L. Verdc) in South Africa. J Agric Sci. 2016;8(11):69-80. https://doi.org/10.5539/jas.v8n11p69
19. Bandyopadhyay A, Nautiyal P, Radhakrishnan T, Gor H. Role of testa, cotyledons and embryonic axis in seed dormancy of groundnut (*Arachis hypogaea* L.). J Agron Crop Sci. 1999;182(1):37-41. https://doi.org/10.1046/j.1439-037x.1999.00255.x
20. Siwale J, Labuschagne M, Gerrano AS, Mbuma NW. Phenotypic diversity and characterization of the Southern African Bambara groundnut germplasm collection for grain yield and yield components. Agronomy. 2022;12(8):1811. https://doi.org/10.3390/agronomy12081811
21. Kulheri A, Sikarwar R. Identification of fresh seed dormancy in bunch type groundnut genotypes (*Arachis hypogaea* L.). Int J Curr Microbiol Appl Sci. 2019;8(10):568-72. https://doi.org/10.20546/ijcmas.2019.810.062
22. Vishnuprabha RS, Viswanathan PL, Manonmani S, Rajendran L, Selvakumar T. Assessment of maturity over seasons using various indices in groundnut (*Arachis hypogaea* L.). Legume Res. 2022;45(5):580-6. https://doi.org/10.18805/LR-4366
23. Kaba JS, Ofori K, Kumaga F. Inter-relationships of yield and components of yield at different stages of maturity in three groundnut (*Arachis hypogaea* L.) varieties. Int J Life Sci Res. 2014;2(1):43-8.
24. Yoga K, Jerlin R, Begum M. Standardization of dormancy induction treatments in groundnut cv. TMV 7. J Agric Res. 2014:21-5. https://doi.org/10.3923/rjss.2014.21.25.
25. Singh A. Growth and physiology of groundnut. Groundnut Res India. 2004;6:178-212. https://www.researchgate.net/publication/284027853
26. Finch-Savage WE, Leubner-Metzger G. Seed dormancy and the control of germination. New Phytol. 2006;171(3):501-23. https://doi.org/10.1111/j.1469-8137.2006.01787.x
27. Behera S, Padhiary AK, Rout S, Nayak A, Behera D, Nanda PK. Effect of plant growth regulators on morpho-physiological and yield parameters of some sesame (*Sesamum indicum* L.) cultivars. Int J Curr Microbiol Appl Sci. 2017;6(11):1784-809. https://doi.org/10.20546/ijcmas.2017.611.215
28. Matilla AJ. Seed dormancy: molecular control of its induction and alleviation. MDPI. 2020;9:1402. https://doi.org/10.3390/plants9101402
29. Rodríguez-Gacio MdC, Matilla-Vázquez MA, Matilla AJ. Seed dormancy and ABA signaling: the breakthrough goes on. Plant Signal Behav. 2009;4(11):1035-48. https://doi.org/10.4161/psb.4.11.9902

30. Kucera B, Cohn MA, Leubner-Metzger G. Plant hormone interactions during seed dormancy release and germination. Seed Sci Res. 2005;15(4):281-307. https://doi.org/10.1079/SSR2005218

31. Brown CH, Gulden RH, Shirtliffe SJ, Vail SL. A review of the genetic, physiological and agronomic factors influencing secondary dormancy levels and seed vigour in *Brassica napus* L. Can J Plant Sci. 2022;103(2):149-60. https://doi.org/10.1139/CJPS-2022-0155

32. Onwubiko MC, Uguru MI, Chimdi GO. Selection for yield for yield improvement in Bambara groundnut [*Vigna subterranea* (L.) Verdc]. J Plant Breed Genet. 2019;7(2):41-53. https://doi.org/10.33687/pbg.007.02.2822

33. Meyer RS, Purugganan MD. Evolution of crop species: genetics of domestication and diversification. Nat Rev Genet. 2013;14(12):840-52. https://doi.org/10.1038/nrg3605

34. Bakal H, Arıoglu H. Determination of some agronomic and quality traits of peanut varieties with different pod characteristics at different harvesting times in main crop growing season. Turk J Field Crops. 2021;26(1):79-87. https://doi.org/10.17557/tjfc.943931

35. Sari M, Ilyas S, Suhartanto MR, Qadir A. Pre-harvest sprouting on high-level seed dormancy of Bambara groundnut (*Vigna subterranea*) landraces. Biodiversitas J Biol Divers. 2021;22(12). https://doi.org/10.13057/biodiv/d221247

36. Zuza EJ, Muitia A, Amane M, Brandenburg R, Mondjana A. Effect of harvesting time on groundnut yield and yield components in northern Mozambique. J Postharvest Technol. 2017;5(2):55-63.

37. Khan MH, Rafi M, Ramlee SI, Jusoh M, Mamun M. Genetic variability, heritability and clustering pattern exploration of Bambara groundnut (*Vigna subterranea* L. Verdc) accessions for the perfection of yield and yield-related traits. Biomed Res Int. 2020;11:1-31. https://doi.org/10.1155/2020/2195797

38. Kumar N, Ajay B, Dagla M, Rathnakumar A, Radhakrishnan T, Lal C, et al. Multi-environment evaluation of Spanish bunch groundnut genotypes for fresh seed dormancy. 2019. https://doi.org/10.31742/IJGPB.79.3.7

39. King R. The physiology of pre-harvest sprouting-a review. In: Third International Symposium on Preharvest Sprouting in Cereals. CRC Press; 2019. p. 11-21. https://doi.org/10.1201/9780367274719-2

40. Sohn S-I, Pandian S, Kumar TS, Zoclanclounon YAB, Muthuramalingam P, Shilpha J, et al. Seed dormancy and pre-harvest sprouting in rice-an updated overview. Int J Mol Sci. 2021;22(21):11804. https://doi.org/10.3390/ijms222111804

41. Bewley JD, Bradford K, Hilhorst H. Seeds: physiology of development, germination and dormancy. 3rd ed. Springer Science & Business Media; 2012. https://doi.org/10.1007/978-1-4614-4693-4

42. Gubler F, Millar AA, Jacobsen JV. Dormancy release, ABA and pre-harvest sprouting. Curr Opin Plant Biol. 2005;8(2):183-7. https://doi.org/10.1016/j.pbi.2005.01.011

43. Cutler SR, Rodriguez PL, Finkelstein RR, Abrams SR. Abscisic acid: Emergence of a core signalling network. Annu Rev Plant Biol. 2010;61:651-79. https://doi.org/10.1146/annurev-arplant-042809-112122

44. Finkelstein R, Reeves W, Ariizumi T, Steber C. Molecular aspects of seed dormancy. Annu Rev Plant Biol. 2008;59:387-415. https://doi.org/10.1146/annurev.arplant.59.032607.092740

45. Pandey MK, Roorkiwal M, Singh VK, Ramalingam A, Kudapa H, Thudi M, et al. Emerging genomic tools for legume breeding: Current status and future prospects. Front Plant Sci. 2016;7:179-244. https://doi.org/10.3389/fpls.2016.00455

46. Nonogaki M, Nonogaki H. Prevention of preharvest sprouting through hormone engineering and germination recovery by chemical biology. Front Plant Sci. 2017;8:243-83. https://doi.org/10.3389/fpls.2017.00090

47. Pandey MK, Pandey AK, Kumar R, Nwosu CV, Guo B, Wright GC, et al. Translational genomics for achieving higher genetic gains in groundnut. Theor Appl Genet. 2020;133:1679-702. https://doi.org/10.1007/s00122-020-03592-2

48. Tai L, Wang HJ, Xu XJ, Sun WH, Ju L, Liu WT, et al. Pre-harvest sprouting in cereals: genetic and biochemical mechanisms. J Exp Bot. 2021;72(8):2857-76. https://doi.org/10.1093/jxb/erab024

49. Bomireddy D, Sharma V, Senthil R, Reddisekhar M, Shah P, Singh K, et al. Identification of donors for fresh seed dormancy and marker validation in a diverse groundnut mini-core collection. Agronomy. 2024;14(1):112. https://doi.org/10.3390/agronomy14010112

50. Nakamura S, Pourkheirandish M, Morishige H, Kubo Y, Nakamura M, Ichimura K, et al. Mitogen-activated protein kinase kinase 3 regulates seed dormancy in barley. Curr Biol. 2016;26(6):775-81. https://doi.org/10.1016/j.cub.2016.01.024

51. Lin M, Cai S, Wang S, Liu S, Zhang G, Bai G. Genotyping-by-sequencing (GBS) identified SNP tightly linked to QTL for pre-harvest sprouting resistance. Theor Appl Genet. 2015;128:1385-95. https://doi.org/10.1007/s00122-015-2513-1

52. Vishwakarma MK, Pandey MK, Shasidhar Y, Manohar SS, Nagesh P, Janila P, et al. Identification of two major quantitative trait loci for fresh seed dormancy using the diversity arrays technology-seq based genetic map in Spanish-type peanuts. Plant Breed. 2016;135(3):367-75. https://doi.org/10.1111/pbr.12360

53. Esan VI, Oke GO, Ogunbode TO. Genetic variation and characterization of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] accessions under multi-environments considering yield performance. Sci Rep. 2023;13:149-58. https://doi.org/10.1038/s41598-023-28794-8

54. Bhat R, Hunje R, Bharath S. Fresh seed dormancy in groundnut: mechanisms and implications—a review. Seed Res. 2020;52(1):1-8. https://doi.org/10.56093/sr.v52i1.158726

55. Yang H, Luo L, Li Y, Li H, Zhang X, Zhang K, et al. Fine mapping of qAHPS07 and functional studies of AhRUVBL2 controlling pod size in peanut (*Arachis hypogaea* L.). Plant Biotechnol J. 2023;21(9):1785-98. https://doi.org/10.1111/pbi.14076

56. Yaw AJ, Richard A, Safo-Kantanka O, Adu-Dapaah HK, Ohemeng-Dapaah S, Agyeman A. Inheritance of fresh seed dormancy in groundnut. Afr J Biotechnol. 2008;7(4).

57. Upadhyaya H, Nigam S, Reddy A, Yellaiah N. Registration of early-maturing fresh seed dormant peanut germplasm ICGV 93470. Crop Sci. 2001;41(2):597. https://doi.org/10.2135/cropsci2001.412597-ax

58. Issa F, Danièl F, Jean-François R, Hodo-Abolo T, Ndoye SM, Tahir DA, et al. Inheritance of fresh seed dormancy in Spanish-type peanut (*Arachis hypogaea* L.). Afr J Biotechnol. 2010;9(13):1905-10. https://doi.org/10.5897/AJB09.1321

59. Zhang M, Zeng Q, Liu H, Qi F, Sun Z, Miao L, et al. Identification of a stable major QTL for fresh-seed germination on chromosome Arahy.04 in cultivated peanut (*Arachis hypogaea* L.). Crop J. 2022;10(6):1767-73. https://doi.org/10.1016/j.cj.2022.03.012

60. Xu P, Tang G, Cui W, Chen G, Ma CL, Zhu J, et al. Transcriptional differences in peanut (*Arachis hypogaea* L.) seeds at freshly harvested, after-ripening and germinated stages. PLoS One. 2020;15(1):e0219413. https://doi.org/10.1371/journal.pone.0219413

61. Bonny SK, Seka D, Adjoumani K, Koffie KG, Kouonon LC, SIie RS. Evaluation of diversity in qualitative traits of Bambara groundnut (*Vigna subterranea* (L.) Verdc.) of Côte d'Ivoire. Afr J Biotechnol. 2019;18(1):23-36. https://doi.org/10.5897/AJB2018.16691

62. Faye I, Ndoye O, Diop T. Evaluation of fresh seed dormancy on seven peanut (*Arachis hypogaea* L.) lines derived from Spanish varieties. J Appl Sci Res. 2009;5(7):853-7.

63. Kumar N, Ajay BC, Rathanakumar AL, Radhakrishnan T, Lal C, Samdur MY, et al. Genetic variability for fresh seed dormancy in Spanish bunch groundnut (*Arachis hypogaea* L.). J Oilseeds Res. 2017;34:119-24. https://doi.org/10.56739/jor.v34i3.137749

64. Ali F, Qanmber G, Li F, Wang Z. Updated role of ABA in seed maturation, dormancy and germination. J Adv Res. 2022;35:199-214. https://doi.org/10.1016/j.jare.2021.03.011

65. Xu F, Tang J, Gao S, Cheng X, Du L, Chu C. Control of rice pre-harvest sprouting by glutaredoxin-mediated abscisic acid signaling. Plant J. 2019;100(5):1036-51. https://doi.org/10.1111/tpj.14501

66. Gerjets T, Scholefield D, Foulkes MJ, Lenton JR, Holdsworth MJ. Analysis of dormancy and ABA responsiveness in wheat (*Triticum aestivum* L.). J Exp Bot. 2010;61(2):597-607. https://doi.org/10.1093/jxb/erp329

67. Leymarie J, Robayo-Romero ME, Gendreau E, Benech-Arnold RL, Corbineau F. ABA involvement in secondary dormancy induction in barley (*Hordeum vulgare* L.) seeds. Plant Cell Physiol. 2008;49(12):1830-8. https://doi.org/10.1093/pcp/pcn164.

68. Kermode AR. Role of abscisic acid in seed dormancy. J Plant Growth Regul. 2005;24:319-44. https://doi.org/10.1007/s00344-005-0110-2

69. Vanitha C, Indira MK, Kathiravan M, Sundareswaran S. Physiological and biochemical basis of seed dormancy in groundnut (*Arachis hypogaea* L.) cultivars. Seed Res. 2021;51(2):76–84. https://doi.org/10.56093/sr.v51i2.154697

70. Dasanal K, Deshpande VK, Motagi BN, Bhat RS, Uppar DS. Effect of maleic hydrazide foliar application on biochemical parameters and phytohormonal variations in groundnut (cv. Dh 86). J Exp Agric Int. 2024;46(12):12–21. https://doi.org/10.9734/jeai/2024/v46i123106

71. Gadhave P, Shelar V, Munde B. Effect of maleic hydrazide on inducing dormancy in green gram (*Vigna radiata* L.). J Food Legumes. 2017;30(1):61–3. https://doi.org/10.59797/journaloffoodlegumes.v30i1.145

72. Shelar VR, Karjule AP, Jayadeva B. Induction of dormancy in groundnut-A review. Agric Rev. 2014;35(3):216–24. https://doi.org/10.5958/0976-0741.2014.00908.8

73. Güllüoğlu L. Effects of growth regulator applications on pod yield and some agronomic characters of peanut in the Mediterranean region. Turk J Field Crops. 2011;16(2):210–4. https://doi.org/10.17557/TJFC.22425

74. Venezian A, Dor E, Achdari G, Plakhine D, Smirnov E, Hershenhorn J. The influence of the plant growth regulator maleic hydrazide on Egyptian broomrape early developmental stages and its control efficacy in tomato under greenhouse and field conditions. Front Plant Sci. 2017;16(8):691–99. https://doi.org/10.3389/fpls.2017.00691

75. Haber AH, White JD. Action of maleic hydrazide on dormancy, cell division and cell expansion. Plant Physiol. 1960;35(4):495. https://doi.org/10.1104/pp.35.4.495

76. Gupta R, Singh S, Verma M. Introduction of dormancy in groundnut (*Arachis hypogaea* L.) variety T64 by maleic hydrazide. Indian J Agric Res. 1985;:82–6. https://api.semanticscholar.org/CorpusID:87290588

77. Mishra J, Mohapatra PD, Sekhar S. Effect of foliar spray of maleic hydrazide on biochemical traits of groundnut seeds. Pharma Innov. 2022;11(11):547–52.

78. Hoffman I, Parups EV. Mode of action of maleic hydrazide in relation to residues in crops and soils. Rev Environ Contam Toxicol. 1964;:96–113. https://doi.org/10.1007/978-1-4615-8389-9_6

79. Jayadeva B, Shelar V, Nagawade D. Effect of maleic hydrazide on groundnut (*Arachis hypogaea*) seed quality. J Food Legumes. 2015;28(4):351–5. http://www.isprd.in/pdf/jfldec15_180117.pdf

80. Mishra J, Swain S. Application of MH to prevent pre-harvest sprouting of seeds in groundnut. Int J Curr Microbiol Appl Sci. 2019;8(9):15–25. https://doi.org/10.20546/ijcmas.2019.809.003

81. Evenari M. Germination inhibitors. Bot Rev. 1949;15:153–94. https://doi.org/10.1007/BF02861721

82. Pirasteh-Anosheh H, Emam Y, Ashraf M. Impact of cycocel on seed germination and growth in some commercial crops under osmotic stress conditions. Arch Agron Soil Sci. 2014;60(9):1277–82. https://doi.org/10.1080/03650340.2013.879119

83. Sadeghi F, Sohrabi Y, Mardeh ASS. Effects of plant growth regulators on seed germination and biochemical properties of two wheat cultivars under water deficit conditions. Gesunde Pflanzen. 2023;75(4):1121–32. https://doi.org/10.1007/s10343-022-00803-2

84. Rajan D, Kumar R, Devyani K, Ramya MJ. Role of ethrel and storage in dormancy breaking in groundnut (*Arachis hypogaea* L.). Int J Curr Microbiol Appl Sci. 2020;9(2):2550–64. https://doi.org/10.20546/ijcmas.2020.902.291

85. Pateliya C, Parmar B, Tandel Y. Effect of different growth retardants on flowering, yield and economics of okra (*Abelmoschus esculentus* L. Moench) cv. GO-2 under South Gujarat conditions. Asian J Hortic. 2008;3(2):317–8.

86. Kumari A, Singh SK, Khan I. Effect of various exogenous salicylic acid concentration on wheat seed germination. Int J Chem Stud. 2020;8:2302–5. https://doi.org/10.22271/chemi.2020.v8.i1ai.8611

87. Vijay CR, Thriveni MC, Shivamurthy GR. Effect of growth regulators on seed germination and its significance in the management of *Aeginetia indica* L.-A root holoparasite. Am J Plant Sci. 2012;3:1490–4. https://doi.org/10.4236/ajps.2012.310179

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.