

ROLE OF UV RADIATION IN SEED PHYSIOLOGY, DORMANCY AND SEEDLING VIGOUR IN LEGUME CROPS

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ABSTRACT

Legume crops (Fabaceae) are fundamental to global food security and soil sustainability, yet their productivity is frequently constrained by seed dormancy, poor germination uniformity and suboptimal early seedling establishment. Ultraviolet (UV) radiation encompassing UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (100–280 nm) is an important environmental and technological factor that significantly modulates seed physiology and early growth. This review synthesizes current knowledge on the role of UV radiation in legume seed biology, encompassing seed coat structural responses, water imbibition, membrane stability, reserve mobilization, antioxidant defense and dormancy regulation. Evidence from major legume crops including soybean (*Glycine max*), mung bean (*Vigna radiata*), black gram (*Vigna mungo*), Bengal gram (*Cicer arietinum*), horse gram (*Macrotyloma uniflorum*) and groundnut (*Arachis hypogaea*) indicates that moderate, controlled UV exposure can break physical dormancy by inducing micro-structural modifications in the seed coat, enhance germination rate and speed, stimulate hydrolytic enzyme activity and promote early seedling vigor. At the molecular level, UV radiation activates the UVR8–HY5 signalling pathway, triggers DNA repair mechanisms, upregulates phenylpropanoid and flavonoid biosynthesis and modulates the abscisic acid–gibberellic acid hormonal balance. These responses are strongly dose-dependent and species or genotype-specific; while low to moderate UV doses elicit adaptive, growth-promoting effects, excessive exposure generates oxidative stress, membrane damage and growth inhibition. Overall, UV radiation presents a promising, non-chemical, eco-friendly approach for seed invigoration and dormancy management in legume-based cropping systems, with significant potential for sustainable agricultural application.

KEYWORDS: Ultraviolet radiation, Legume seeds, Seed dormancy, Seed physiology, Germination and Seedling vigour.

1. INTRODUCTION

Legume crops belonging to the family Fabaceae play a vital role in global agriculture due to their dual function in food security and soil fertility improvement. These crops, commonly known as pulses, are rich in plant-based proteins, dietary fiber, essential amino acids, minerals (iron, zinc), and bioactive compounds, making them a cornerstone in human nutrition, particularly in developing countries (FAO). In addition, legumes possess the unique ability to fix atmospheric nitrogen through symbiosis with rhizobia, thereby enhancing soil health and sustainability of cropping systems. Seeds are the fundamental units of plant propagation, ensuring survival, dispersal and regeneration. They contain stored reserves that support early seedling growth and exhibit dormancy mechanisms that allow them to withstand unfavorable environmental conditions. However, in many legume crops, seed dormancy- especially physical dormancy due to hard seed coats-poses a major constraint, leading to poor and non-uniform germination, ultimately reducing crop establishment and yield (Zhaozhu Wen *et al.*, 2024). To overcome these limitations, modern seed technologies have focused on seed invigoration techniques, among which physical methods such as ultraviolet (UV) radiation are gaining increasing attention. Ultraviolet radiation, particularly UV-A, UV-B and UV-C wavelengths, acts as an environmental signal that can significantly influence plant physiological processes, including enzyme activation, hormonal balance and metabolic pathways (Foroughbakhchet *et al.*, 2019).

Recent studies have demonstrated that controlled exposure of seeds to UV radiation can modify seed coat permeability, enhance enzymatic activity, and stimulate germination. UV treatment can break seed dormancy by weakening the seed coat and increasing internal seed temperature, thereby facilitating water uptake and embryo growth (Upadhyay *et al.*, 2020). Furthermore, UV radiation influences biochemical pathways by inducing the synthesis of antioxidants, flavonoids, and protective compounds, which improve seedling vigor and stress tolerance (Hamid *et al.*, 2023). However, the effects of UV radiation are dose-dependent. While optimal doses can enhance germination, vigor and early seedling growth, excessive exposure may lead to oxidative damage, reduced photosynthetic efficiency, and impaired growth (Babak Peykarestan *et al.*, 2012). Thus, understanding the balance between beneficial and harmful effects is crucial for its practical application in agriculture. From a nutritional perspective, improved germination and early growth induced by UV treatments can enhance the

nutritional quality of legumes. Germination activates hydrolytic enzymes that degrade antinutritional factors such as phytates and trypsin inhibitors, thereby improving nutrient bioavailability, digestibility and accumulation of health-promoting compounds (ChamodiGunathunga *et al.*, 2024). Additionally, sprouted legumes exhibit increased levels of vitamins, antioxidants, and functional metabolites, contributing to better human health outcomes (Yingjinzhu Wu & Weon-Sun Shin., 2025). Despite these advantages, challenges remain in optimizing UV-based treatments for different legume species, as their responses vary depending on seed structure, dormancy type and environmental conditions. Therefore, integrating UV radiation as a seed priming strategy offers a promising, eco-friendly approach to improve seed physiology, break dormancy and enhance early growth in legume crops.

2. Ultraviolet radiation: nature and biological significance

2.1 Classification of UV radiation (UV-A, UV-B and UV-C)

Ultraviolet (UV) radiation forms an important fraction of the solar electromagnetic spectrum ranging from (100-400 nm) with a higher frequency but shorter wavelength than visible light (400-700nm). Based on the wavelength range and biological activity it can be classified into three viz., UV- A (315-400nm), UV-B (280-315 nm) and UV-C (100- 280nm). UV-A possesses relatively low photon energy and primarily functions as a regulatory signal influencing photomorphogenesis, circadian rhythms and secondary metabolites. UV-B radiation is more energetic and biologically active, capable of inducing DNA damage, oxidative stress and alterations in plant growth and development, while it is also acting as a signaling stimulus at low doses. UV-C radiation is also the most energetic and potentially lethal, causing severe DNA and cellular damage; however, it is almost completely absorbed by the stratospheric ozone layer and therefore does not occur naturally at the earth's surface (WHO, 1979; Teramura & Murali., 1986).

2.2 Natural and artificial sources of UV radiation

The main natural source of UV radiation is sunlight. Its intensity changes depending on factors like latitude, altitude, season, time of day, cloud cover and the amount of ozone in the atmosphere. When the ozone layer becomes thinner, more biologically active UV-B radiation reaches the ground, which can affect agriculture. Studies in fields and greenhouses have found that higher levels of solar UV-B can reduce plant height, leaf area, and biomass in crops such as soybean (*Glycine max*) and green gram (*Vigna radiata*), which can lower yields (Teramura *et al.*, 1987; Rajendiran *et al.*, 2015). Besides natural sources, artificial UV radiation is often used in plant research and seed technology. UV-B lamps help mimic increased solar UV-B, while UV-C lamps (254 nm) are used to sterilize seeds, change dormancy and boost seed performance. For example, UV-C treatment can improve germination and seedling strength in maize (*Zea mays*), sugar beet (*Beta vulgaris*) and mung bean if used for the right amount of time. However, too much exposure can harm the plants (Sadeghianfaret *et al.*, 2019; Hernandez-Aguilar *et al.*, 2021).

2.3 Penetration and perception of UV radiation in plant tissues

The penetration and perception of UV radiation in plant tissues are largely governed by wavelength, tissue anatomy and biochemical composition. Short-wavelength UV-C and UV-B radiation exhibits limited penetration due to strong absorption by surface tissues such as the cuticle, epidermis and seed coat, whereas UV-A can penetrate deeper into mesophyll tissues. In seeds, particularly legumes the testa acts as a major barrier to UV penetration owing to the presence of thick palisade layers enriched with lignin, suberin, waxes and phenolic compounds, thereby confining UV effects primarily to the seed surface (Smykal *et al.*, 2014). This structural property explains why UV-C seed treatments often modify seed coat permeability and enhance water uptake without deeply damaging the embryo, as observed in soybean and Bengal gram (*Cicer arietinum*) seeds (Upadhyay *et al.*, 2020; Sadeghianfaret *et al.*, 2019).

Plants perceive UV-B radiation through the UV RESISTANCE LOCUS 8 (UVR8) photoreceptor, which initiates signalling cascades leading to the accumulation of UV-absorbing compounds such as flavonoids and phenolic acids. These compounds function as protective screens, reducing UV penetration into underlying tissues and scavenging reactive oxygen species generated during UV exposure (Jenkins, 2014; Yang *et al.*, 2020). Crop-specific evidence indicates that moderate UV exposure induces adaptive responses, such as increased phenolic content in mung bean and enhanced antioxidant activity in soybean, thereby improving stress tolerance and early seedling performance. Conversely, prolonged or high-intensity UV exposure overwhelms protective mechanisms, resulting in DNA damage, membrane lipid peroxidation and growth inhibition, as reported in horse gram (*Macrotyloma uniflorum*) and lupin (*Lupinus mutabilis*) (Falconi *et al.*, 2019; De *et al.*, 2022). These findings demonstrate that plant responses to UV radiation are strongly dose-dependent and species-specific, reflecting differences in tissue penetration, perception mechanisms and protective capacity.

3. Sensitivity of legume seeds to ultraviolet radiation

3.1 Structural characteristics of legume seed coats influencing UV response

Legume seeds show different levels of sensitivity to ultraviolet (UV) radiation mainly because of variations in the structure, thickness and makeup of their seed coats. The seed coat (testa) in legumes generally consists of a well- formed palisade layer (macroscleireids), hourglass cells and an outer cuticular layer enriched with lignin, suberin and waxes. These elements function as a physical barrier against radiation penetration. Hard- seeded legumes like soybean (*Glycine max*), Chickpea (*Cicer arietinum*) and mung bean (*Vigna radiata*) possess thicker palisade layer and more continuous cuticles, which limit UV penetration to the outer tissues and

safeguard the embryo from direct harm (Smykal *et al.*, 2014). Research findings suggest that UV- C seed treatments primarily target the testa by creating micro-cracks or modifying cuticular permeability, thus improving water absorption and germination without harming the internal tissues, as seen in soybean and mung bean seeds subjected to specific UV- C concentrations (Hernandez-Aguilar *et al.*, 2021; Sadeghaianfaret *al.*, 2019). In contrast, legumes with thinner or less lignified seed coats have a higher sensitivity to UV, as the weakened physical barrier permits more profound penetration of UV-B and UV-C radiation, leading to decreased germination and damaged to seedlings.

3.2 Variability in UV Sensitivity by species and Genotype

The response of legume seeds to UV radiation is largely determined by their species and genotype, which is a reflection of the genetic variations in seed coat design, ability to manage antioxidants and mechanisms for repair. For instance, Bengal gram (*Cicer arietinum*) seeds demonstrate better germination and stonger seedling growth after brief exposure to UV-C, while horse gram (*Macrotyloma uniflorum*) shows notable declines in germination, chlorophyll levels and overall biomass under the same conditions, indicating a higher sensitivity to UV (Upadhyay *et al.*, 2020). In soybean, differences among varieties have been observed regarding their reaction to increased UV-B radiation with some types experiencing significant decreases in seed size and yield due to a reduction in the number of cotyledon cells, while others have more moderate reactions (Teramura&Murali., 1986; Chen *et al.*, 2013). Likewise there are variations among green gram types in terms of their UV-B exposure tolerance, with resilient genotypes exhibiting greater growth rates and antioxidant levels compared to those that are more sensitive (Rajendiran *et al.*, 2015). These findings imply that UV sensitivity in legumes is influenced by both the species and the specific genetic characteristics that affect how they perceive radiation, repair damage and adjust their metabolism.

3.3. Function of seed coat colors and phenolic substances in shielding against UV radiation.

Pigments in seed coats and phenolic substances are essential for protecting legume seeds from damage caused by UV radiation by absorbing harmful rays and removing reactive oxygen species. Typically dark-colored legume seeds have higher levels of phenolics, flavonoids and tannins, which act as natural barriers against UV light and serve as antioxidants. Research involving mung beans and black gram (*Vigna mungo*) has shown that exposure to UV-B light leads to increased levels of free phenols, flavonoids and anthocyanin in both seed coats and seedlings, providing better defense against oxidative stress (Rajendiranet *al.*, 2013; De *et al.*, 2022). In soybeans, the heightened production of flavonoids when exposed to UV-B radiation has been associated with less cellular harm and greater resilience, emphasizing the protective function of phenylpropanoid pathways (Jenkins 2014). On the other hand legumes with fewer phenolic compounds or lighter seed coat colors are more prone to UV related damage to membranes and show decreased germinations rates, as seen in horse gram and some species of lupins (Falconi *et al.*, 2019). Therefore, the existence and ability to increase phenolic compounds in the coats of legume seeds represent a vital biochemical adaptation that affects UV sensitivity and influences both seed survival and early development under UV stress.

4.Effects of UV light on Seed Physiology in Legumes

4.1 Alterations in moisture absorption and imbibition characteristics

Ultraviolet (UV) light has a major effect on how legumes absorb moisture and their imbibition characteristics by changing the physical and chemical features of the seed coat. Studies indicate that exposure to UV-C or moderate UV-B light can boost permeability of the seed coat by altering the micro structure of the cuticle and palisade layers, which facilitates water intake during the early germination stage. In species like soybean (*Glycine max*) and mung bean (*Vigna radiata*), brief exposure to UV-C light led to a quicker imbibition rate and speed up germination, likely due to partial damage to hydrophobic seed coat elements such as waxes and cutin (Sadeghaianfaret *al.*, 2019; Hernandez-Aguilar *et al.*, 2021). Likewise, Bengal gram (*Cicer arietinum*) seeds showed enhanced water absorption and better germination after being exposed to controlled UV light, suggesting that UV radiation has a scarification like impact on tough seed coats (Upadhyay *et al.*, 2020). However, extended or high level UV exposure can damage the seed coat excessively, resulting in unregulated water intake and hindered germination, as observed in horse gram (*Macrotyloma uniflorum*), underscoring the importance of dosage in UV impacts on imbibition.

4.2 Modification of membrane stability and electrolyte loss

The integrity of seed membranes is crucial for seed vitality and is particularly susceptible to ultraviolet light. Damage to membrane lipids caused by UV leads to higher permeability and electrolyte loss during soaking, which is often used as a sign of membrane disruption. Research on legume seeds indicates that moderate UV exposure can preserve or even enhance membrane structure by activating repair processes, while excessive exposure results in lipid degradation and solute leakage. In green gram (*Vigna radiata*), low UV-C levels helped maintain membrane integrity and decreased leakage during the initial stages of germination, whereas higher levels led to significant electrolyte loss indicating oxidative damage to the membranes (Rajendiran *et al.*, 2015). On the other hand, horse gram seeds showed notable electrolyte leakage even with low UV exposure, corresponding with poorer germination and seedling growth (Gandhi *et al.*, 2019). These results suggest that variations in membrane composition and antioxidant levels between species play a significant role in how severely UV light impacts membrane damage in legumes.

4.3 Impacts on seed metabolic function and respiration

UV light affects seed metabolic processes by altering respiratory functions and enzyme activation during germination. Increased metabolic rates following moderate UV exposure are commonly linked with elevated respiration, which signifies quicker mobilization of seed nutrients. In soybean and mung bean, UV-C treatment boosted respiratory activity in the early germination phase, resulting in quicker radicle emergence and better seedling health (Sadeghianfare et al., 2019; Hernandez Aguilar et al., 2021). This encouraging effect is due to UV induced stimulation of enzymes like amylases and proteases, which aid in swiftly converting stored nutrients into usable energy. In contrast, too much UV exposure shortens and delays germination, as seen in lupin (*Lupinus mutabilis*) and horse gram (Falconi et al., 2019). Therefore UV radiation has a dual effect on seed metabolism, increasing respiration at lower doses while hindering metabolic rates at higher levels.

4.4 UV- triggered oxidative stress and responses of antioxidant enzymes

A major physiological effect of UV radiation on legume seeds is the creation of oxidative stress caused by the production of reactive oxygen (ROS), which includes superoxide radicals, hydrogen peroxide and hydroxyl radicals. At moderate levels, ROS serve as signaling agents that trigger antioxidant defense mechanisms; however, when ROS levels become too high, they can harm lipids, proteins and nucleic acids. In mung bean and black gram (*Vigna mungo*) exposure to UV-B significantly boosted the activity of antioxidant enzymes like superoxide dismutase, catalase and peroxidase, along with an increase in the levels of phenolic compounds, thereby enhancing their resilience to UV- induced stress (Rajendiran et al., 2013; De et al., 2022). Likewise soybean seeds that were subjected to UV-B showed an increase in flavonoid production and antioxidant enzyme activity, which helped reduce oxidative damage during the early stages of seedling growth (Teramura&Murali., 1986). On the other hand, UV sensitive legumes, such as horse gram, exhibited inadequate antioxidant responses, which led to oxidative damage to cell membranes and lower germination rates (Gandhi et al., 2019). These responses that vary among crops highlight the crucial role of antioxidant capacity in influencing the effects of UV exposure on legume seeds.

5.Role of UV Radiation in Controlling Seed Dormancy

5.1 Physical dormancy and changes in the seed coat caused by UV

Physical dormancy is a common type of dormancy in legumes, mainly caused by a seed coat that does not allow water to enter, which consists of thick palisade layers, cuticular waxes, lignin and phenolic compounds. Ultraviolet (UV) radiation, especially UV-C and UV-B has been shown to affect physical dormancy by causing structural and chemical modifications in the seed coat. Controlled exposure to UV modifies the cuticle's integrity and opens up palisade cells, leading to decreased hydrophobicity and increased permeability for water and gases. Research on soybean (*Glycine max*), Bengal gram (*Cicer arietinum*), and mung bean (*Vigna radiata*) has shown that brief UV-C exposure effectively breaks physical dormancy and boosts germination without harming the embryo similar to mechanical scarification (Sadeghianfare et al., 2019; Hernandez-Aguilar et al., 2021). These results suggest that UV radiation primarily operates at the seed coat level to remove physical barriers that keep legume seeds dormant.

5.2 UV induced microcracks and changes in permeability in hard- seeded legumes

One of the main ways that UV radiation aids in breaking dormancy in hard seeded legumes is by creating tiny cracks and irregularities on the seed coat surface. Studies using scanning electron microscopy have shown that UV-C exposure leads to localized cracks and pits within the palisade layer, allowing water to enter through specific areas like the lens, hilum and micropylary. In hard seeded varieties such as chickpea (*Cicer arietinum*) black gram (*Vigna mungo*) and groundnut (*Arachis hypogea*), seeds that have been treated with UV displayed enhanced water absorption rates and increased germination percentages compared to untreated seeds (Upadhyay et al., 2020; Rajendiran et al., 2013). However excessive exposure to UV can cause severe damage to the seed coat, resulting in uncontrolled water absorption, solute leakage and lower seed viability, as seen in horse gram, (*Macrotyloma uniflorum*). Thus changes in permeability due to UV are only advantageous within a specific range of exposure, emphasizing the need for careful dosage regulation.

5.3 Interaction of UV radiation with temperature and moisture in dormancy release

The role of UV radiation in managing seed dormancy is significantly affected by its relationship with environmental elements like temperature and moisture. In natural habitats, the release of dormancy in legumes typically takes place due to the combined influence of sunlight, varying temperatures and soil moisture levels. UV radiation aids in the breakdown of dormancy by softening the seed coat, while subsequent exposure to moisture and temperature changes encourages water uptake and growth of the embryo. Research has demonstrated that seeds of mung beans and soybeans treated with UV show better germination rates when followed by suitable moisture and moderate temperatures, while UV exposure by itself in dry conditions does not effectively trigger dormancy release (Rajendiran et al., 2015; Teramura&Murali., 1986). Likewise, cycles of alternating wet and dry conditions after UV treatment were observed to work together to further enhance dormancy release in hard-seeded legumes, suggesting that UV radiation acts as a supportive factor rather than a solitary trigger in the process of dormancy control.

5.4 Hormonal control of dormancy when exposed to UV light (ABA and GA balance)

Besides impacting the seed coat physically, UV light also affects how dormancy is managed by changing hormone levels, especially by adjusting the ratio of abscisic acid (ABA) to gibberellic acid (GA). ABA is the key hormone that keeps seeds in a dormant state, while GA encourages germination by promoting embryo growth and the use of nutrient reserves. Research has shown that exposure to UV-B light led to a decrease in ABA in developing and sprouting seeds, resulting in less dormancy and quicker germination (Teramura&Murali, 1986). Likewise, mung bean seeds treated with UV showed heightened GA related enzyme activity, such as increased amylase labels, which speed up the mobilization of reserves and the emergence of the radicle (De *et al.*, 2022). However, too much exposure to UV light can upset hormonal balance by causing oxidative stress, which can hinder GA effectiveness, reinforce dormancy, or even damage the seed, as seen in UV sensitive legumes like horse gram. These results illustrate that UV light affects dormancy through both physical changes to the seed coat and changes in hormone levels, with the balance between ABA and GA being crucial.

6. Effects of UV Radiation on Germination Behavior

6.1 Germination rate and speed under UV light

Ultraviolet (UV) radiation has a notable effect on the percentage of seed germination and the speed of germination in legumes, with responses highly influenced by the type and amount of radiation, as well as the specific species. Multiple studies have shown that brief exposure to UV-C or moderate UV-B can improve the germination rate and quicken the process by enhancing seed coat permeability and stimulating early metabolic processes. In mung beans (*Vigna radiata*) and soybeans (*Glycine max*) pretreating with UV-C led to an increase in the speed and consistency of germination, resulting in quicker radicle growth than untreated seeds (Sadeghianfaret *et al.*, 2019; Hernandez-Aguilar *et al.*, 2021). Similarly, seeds of maize (*Zea mays*) and sugar beet (*Beta vulgaris*) that were exposed to controlled doses of UV-C did not see a decreases in final germination rates but did show a marked increase in germination speed, suggesting improved seed vitality (Sadeghianfaret *et al.*, 2019). In contrast, extended or high intensity UV exposure reduced germination rates in UV-sensitive legumes such as horse gram (*Macrotyloma uniflorum*) and lupin (*Lupinus mutabilis*) where excessive oxidative stress hindered the viability of the embryo (Falconi *et al.*, 2019). These results indicate that UV radiation can either promote or hinder germination based on the conditions of exposure and the sensitivity of the crop.

6.2 Changes in enzyme activities linked to resource mobilization

UV radiation affects germination patterns by altering the function of enzymes necessary for utilizing stored nutrients, which is essential for seedling growth. Studies have shown that moderate levels of UV exposure can activate hydrolytic enzymes like α -amylase, protease and lipase, improving the breakdown of stored carbohydrates, proteins and fats during the germination process. In seeds of soybean and mung bean treated with UV, there was a notable increase in amylase activity, which speed up the breakdown of starch and made soluble sugars more available to the developing embryo (Hernandez-Aguilar *et al.*, 2021 De *et al.*, 2022). Short treatments of UV-C on Bengal gram (*Cicer arietinum*) seeds resulted in elevated protease activity and better seedling growth, demonstrating improved use of reserves (Upadhyay *et al.*, 2020). In contrasts, excessive exposure to UV light harmed proteins and cell membranes, which led to reduced or delayed germination, seen in horse gram and lupin (Falconi *et al.*, 2019). Therefore, the changes in enzyme activity caused by UV light are a significant physiological factor that affects the germination behavior of legumes.

6.3 Different impacts of UV-A, UV-B and UV-C on seed germination

The influence of UV light on seed germination shows significant differences among the UV-A, UV-B, UV-C ranges because of variations in photon energy and how deep they can penetrate. Usually, UV-A causes little direct harm and can have a moderating effect, sometimes promoting germination through its interaction with blue light receptors. UV-B, being more potent, can either boost or hinder germination depending on the exposure level, low amounts of UV-B have been known to trigger protective signaling and antioxidant reactions, while high amounts of UV-B can inhibit germination by damaging DNA and cell membranes. In soybean and green gram, increased levels of UV-B stunted seedling growth but did not necessarily lead to a significant change in germination rate, suggesting that the process of germination is more robust than the growth that follows (Termura&Murali., 1986; Rajendiran *et al.*, 2015). UV-C which is not found in natural sunlight, is often utilized as an artificial treatment for seeds and usually has the most noticeable effects on germination. Short exposure of UV-C has been shown to enhance the speed and vigor of germination in mung bean, maize, and sugar beet, while continuous exposure can be fatal for young seedlings, demonstrating the potent biological activity of this type of light (Sadeghianfaret *et al.*, 2019; Hernandez-Aguilar *et al.*, 2021)

6.4 Dose dependent effects that stimulate and inhibit from UV radiation

A key aspect of how UV radiation affects germination is the dose dependent biphasic response, often referred to as hormesis. Low to moderate doses of UV act as a positive signal, improving germination rate, antioxidant defenses and metabolic processes. This positive effect has been observed in mung bean, soybean Bengal gram and groundnut (*Arachis hypogea*) when exposed to brief UV-C or moderate UV-B (Rajendiran *et al.*, 2013; Sadeghianfaret *et al.*, 2019). Conversely, high levels of UV radiation can overwhelm cellular defense mechanism resulting in a buildup of harmful reactive oxygen species, damage to membranes, enzyme malfunction and DNA harm, ultimately leading to decreased germination and increased seed death. Such negative effects have been clearly demonstrated in horse gram and lupin under extended exposure to UV (Falconi *et al.*, 2019). These

results underscore that UV radiation acts as a double edged sword in controlling germination, with the biological results affected by the dose type of UV light and the specific tolerance of each species.

7. Seedling Vigour in Legume Crops

Seedling vigour is a composite attribute that reflects the capacity of a seed lot to produce uniform, rapid and robust seedlings under a wide range of field conditions. It integrates multiple physiological and biochemical properties including germination speed, radicle length, shoot elongation, dry weight accumulation, enzyme activity and stress tolerance during the critical post-germination phase. In legume crops, seedling vigour is of particular agronomic importance as it determines the uniformity of crop stand establishment, early canopy closure, competitive advantage over weeds and ultimately the potential for higher grain yield. The International Seed Testing Association (ISTA) defines seed vigour as those properties that determine the potential for rapid, uniform emergence and development of normal seedlings under a wide range of field conditions (ISTA, 2021). In legumes, vigour is shaped by a combination of genetic factors, seed maturation conditions, post-harvest handling and pre-sowing seed treatments.

Seedling vigour in legumes is closely linked to the efficiency of storage reserve mobilization during germination. Legume seeds store reserves primarily as proteins and lipids in cotyledons, and the rapid hydrolysis of these reserves by amylases, proteases and lipases is a prerequisite for vigorous seedling development. High vigour seeds exhibit superior enzymatic activity, ensuring faster conversion of stored nutrients into energy and structural components for growing seedling axes. In soybean (*Glycine max*), seed vigour has been positively correlated with protease and amylase activity during early germination, and high-vigour seed lots demonstrated superior seedling dry weight and shoot length at 7 days after sowing compared to low-vigour lots (Marcos-Filho, 2015). Similarly, in mung bean (*Vigna radiata*), enhanced seedling vigour indices were associated with greater alpha-amylase activity and higher soluble sugar content in the germinating cotyledons, reflecting more efficient carbohydrate mobilization (Sadeghianfaret *et al.*, 2019). Vigour testing methods including the accelerated ageing test, cold test, electrical conductivity test and seedling growth parameters such as the seedling vigour index (SVI) are widely used for quality assessment in legume seed lots (ISTA, 2021; Marcos-Filho, 2015).

UV radiation has been recognized as a significant physical elicitor capable of enhancing seedling vigour in legume crops when applied at optimal doses. UV-C treatment of seeds at controlled exposures has been found to stimulate seedling vigour by promoting faster radicle and plumule emergence, improved shoot and root elongation, and higher seedling dry weight accumulation. In mung bean, seeds treated with UV-C for 5–15 minutes showed significantly higher seedling vigour index values, with vigour index-I and vigour index-II both increasing compared to untreated controls, attributed to UV-induced activation of hydrolytic enzyme systems and improved membrane integrity (De *et al.*, 2022). In Bengal gram (*Cicer arietinum*), UV-C-primed seeds exhibited improved seedling length, root-shoot ratio and fresh weight compared to untreated seeds, suggesting that UV-induced scarification of the seed coat facilitates more uniform and vigorous seedling establishment (Upadhyay *et al.*, 2020). Groundnut (*Arachis hypogaea*) seeds subjected to short UV-C exposures also showed enhanced seedling biomass and vigour, partly due to improved antioxidant enzyme activity that protected seedling tissues against oxidative deterioration (Siddiqui *et al.*, 2011).

Membrane integrity is a central determinant of seedling vigour, as damaged membranes during the early imbibition and germination phases result in excessive electrolyte leakage, impaired cellular compartmentation and reduced metabolic efficiency. Electrical conductivity of seed leachate is routinely used as a vigour test in legumes, with lower conductivity values indicating better membrane integrity and higher vigour (ISTA, 2021). Antioxidant systems including superoxide dismutase (SOD), catalase (CAT), peroxidase (POX) and ascorbate peroxidase (APX), along with non-enzymatic antioxidants such as ascorbic acid, tocopherols and carotenoids, play pivotal roles in protecting seedling tissues from reactive oxygen species (ROS) generated during aerobic germination metabolism (Gill and Tuteja, 2010). In legume seedlings exposed to moderate UV-B radiation, elevated SOD and CAT activity was observed in mung bean and black gram (*Vigna mungo*), correlating with improved seedling growth parameters and reduced lipid peroxidation (Rajendiran *et al.*, 2013; De *et al.*, 2022). These antioxidant responses contribute directly to the vigour of the emerging seedling by limiting oxidative deterioration of cell membranes and proteins in meristematic tissues. Conversely, UV-sensitive legumes such as horse gram (*Macrotyloma uniflorum*) showed inadequate antioxidant defenses under UV stress, leading to chlorophyll degradation, membrane damage and suppressed seedling vigour, underscoring the species-specific nature of UV vigour responses in legumes (Gandhi *et al.*, 2019; Upadhyay *et al.*, 2020).

Photosynthetic competence of young seedlings is another key indicator of vigour in legumes, as efficient chloroplast development and chlorophyll accumulation in the first true leaves determine early carbon assimilation capacity. High-vigour seedlings establish functional photosynthetic machinery sooner after emergence, enabling transition from heterotrophic to autotrophic growth more rapidly. UV-B radiation at elevated doses has been shown to reduce chlorophyll a and b content, inhibit Rubisco activity and reduce the Fv/Fm ratio (a measure of photosystem II efficiency) in soybean and mung bean seedlings, thereby limiting photosynthetic vigour (Teramura&Murali., 1986; Rajendiran *et al.*, 2015). In contrast, low-dose UV-C seed treatment stimulated chlorophyll accumulation and early photosynthetic efficiency in treated mung bean and groundnut seedlings, reflecting enhanced vigour due to improved seed quality and metabolic preparedness (Hernandez-Aguilar *et al.*, 2021; Siddiqui *et al.*, 2011). The interplay between UV-induced reactive oxygen

species, antioxidant defense, phenylpropanoid accumulation and hormonal signalling (particularly gibberellin and cytokinin balance) collectively governs the vigour of legume seedlings exposed to UV radiation (Gill and Tuteja, 2010; Yang *et al.*, 2020). Together, these findings confirm that seedling vigour in legume crops is a multi-dimensional attribute influenced by UV dose, species sensitivity, antioxidant capacity and the integrity of photosynthetic and metabolic systems during the critical post-germination establishment phase.

8. Molecular and Biochemical Mechanisms Underlying UV Responses

8.1 UV-induced DNA damage and repair mechanisms in germinating seeds

Ultraviolet (UV) radiation induces direct and indirect DNA damage in germinating seeds, making efficient repair mechanisms essential for successful seedling establishment. UV-B and UV-C radiation primarily cause the formation of cyclobutane pyrimidine dimers (CPDs) and 6-4 photoproducts in DNA, which interfere with replication and transcription processes. During germination, when cells rapidly divide and DNA replication is active, such lesions can severely impair embryo growth. Studies in soybean (*Glycine max*) and mung bean (*Vigna radiata*) have demonstrated increased DNA damage following UV exposure, accompanied by activation of DNA repair pathways such as photoreactivation mediated by photolyase enzymes and nucleotide excision repair mechanisms (Teramura *et al.*, 1987; De *et al.*, 2022). In germinating green gram seeds, low UV-B exposure induced repair-associated gene expression and promoted endoreduplication, enabling cells to tolerate DNA damage while maintaining growth (De *et al.*, 2022). However, excessive UV exposure overwhelms repair capacity, leading to persistent DNA lesions and reduced germination, as observed in UV-sensitive legumes such as horse gram (*Macrotyloma uniflorum*).

8.2 Activation of UV-responsive genes and transcription factors

UV radiation triggers extensive transcriptional reprogramming in seeds and young seedlings through the activation of UV-responsive genes and transcription factors. The UV-B-specific photoreceptor UV RESISTANCE LOCUS 8 (UVR8) plays a central role in initiating UV-responsive signaling by dissociating into active monomers upon UV-B perception. This activation leads to the regulation of transcription factors such as ELONGATED HYPOCOTYL 5 (HY5), which controls the expression of genes involved in UV protection, antioxidant defense and secondary metabolism. In soybean and mung bean, UV-B exposure significantly upregulated HY5-regulated genes, resulting in increased synthesis of UV-absorbing compounds and stress-responsive proteins (Jenkins, 2014; Yang *et al.*, 2020). Transcriptomic studies in legumes further reveal induction of genes associated with DNA repair, ROS detoxification and phenylpropanoid metabolism, highlighting a coordinated molecular response that supports seedling survival under moderate UV stress.

8.3 Role of secondary metabolites and flavonoids in UV tolerance

Secondary metabolites, particularly flavonoids and other phenolic compounds, constitute a major biochemical defense mechanism underlying UV tolerance in legumes. These compounds accumulate in seed coats, cotyledons and emerging seedling tissues, where they function as natural UV screens by absorbing harmful radiation and scavenging reactive oxygen species (ROS). Crop-wise evidence indicates that UV-B exposure enhances flavonoid biosynthesis in mung bean, black gram (*Vigna mungo*) and soybean, leading to increased antioxidant capacity and reduced cellular damage during early growth stages (Rajendiran *et al.*, 2013; Jenkins, 2014). In germinating mung bean seeds, UV-induced accumulation of phenolics was strongly correlated with improved membrane stability and lower lipid peroxidation levels (De *et al.*, 2022). Conversely, legumes with lower basal or inducible phenolic content, such as horse gram, exhibit higher susceptibility to UV-induced oxidative stress, resulting in impaired germination and seedling growth (Gandhi *et al.*, 2019). These findings underscore the pivotal role of flavonoid-based biochemical shielding in determining UV tolerance across legume species.

8.4 Signalling pathways involved in UV perception and response

UV perception and downstream responses in germinating seeds involve a complex network of signalling pathways integrating light, oxidative and hormonal signals. Upon UV-B perception by UVR8, downstream signalling involves interaction with CONSTITUTIVELY PHOTOMORPHOGENIC 1 (COP1), leading to stabilization of HY5 and activation of UV-responsive genes. Simultaneously, UV-induced ROS function as secondary messengers that modulate MAP kinase cascades and antioxidant signalling pathways. Hormonal cross-talk further refines these responses, particularly through interactions between abscisic acid (ABA), gibberellic acid (GA) and auxins. In soybean, UV-B exposure altered ABA–GA balance, linking UV signalling with dormancy release and early growth regulation (Teramura & Murali., 1986). In mung bean seedlings, coordinated signalling between ROS, phenylpropanoid metabolism and hormonal pathways contributed to enhanced stress acclimation under low UV doses (De *et al.*, 2022). Together, these interconnected signalling networks enable germinating legume seeds to perceive UV radiation accurately and mount adaptive molecular and biochemical responses that balance growth and protection.

9. Research Gaps and Future Perspectives

Despite growing evidence that ultraviolet (UV) radiation can beneficially modulate seed dormancy, germination and early seedling growth in legumes, several critical research gaps remain to be addressed. One major limitation is the lack of **crop and genotype-specific standardization of UV dose, wavelength and exposure duration**. Existing studies report highly variable responses across legume species and even among cultivars within the same species, with low to moderate UV doses exerting stimulatory effects while higher doses cause irreversible damage. However, most studies rely on empirical exposure regimes without establishing physiologically optimized thresholds, making it difficult to translate laboratory findings into practical seed treatment protocols. Systematic dose–response studies across diverse legume genotypes are therefore essential to define safe and effective UV treatment windows for agricultural application.

Another significant gap lies in the **limited understanding of molecular regulation of UV responses in legume seeds**, particularly during the critical transition from dormancy to germination. While UV-induced signalling pathways, DNA repair mechanisms and flavonoid biosynthesis have been extensively studied in model plants, comparable molecular-level investigations in legume seeds remain scarce. There is a need for integrative omics-based approaches, including transcriptomics, proteomics and metabolomics, to elucidate UV-responsive gene networks, transcription factors and hormonal cross-talk specific to legume seed physiology. Such studies would provide mechanistic insights into species- and genotype-dependent UV sensitivity and help identify molecular markers associated with UV tolerance and seed vigor.

Furthermore, considerable scope exists for integrating UV radiation with modern seed technologies to enhance seed quality and sustainability. Combining UV treatment with seed priming, plasma treatment, biostimulants or nanotechnology-based coatings could synergistically improve germination performance, stress tolerance and pathogen resistance while reducing dependence on chemical seed treatments. Future research should focus on evaluating these combined approaches under field conditions, assessing their long-term effects on crop establishment, yield and seed quality. Addressing these research gaps will be crucial for harnessing UV radiation as a precise, eco-friendly and scalable tool in legume seed technology and climate-resilient agriculture.

10. CONCLUSION

The present review highlights the multifaceted role of ultraviolet (UV) radiation in regulating seed physiology, dormancy, germination behaviour and early seedling growth in legumes. Evidence from diverse legume crops demonstrates that UV radiation influences key physiological processes, including seed coat permeability, water imbibition, membrane stability, reserve mobilization and antioxidant defense. At the molecular and biochemical levels, UV exposure induces DNA damage and repair mechanisms, activates UV-responsive genes and transcription factors, enhances phenylpropanoid and flavonoid biosynthesis, and modulates hormonal balance, particularly the interaction between abscisic acid and gibberellic acid. These responses collectively determine whether UV radiation exerts stimulatory or inhibitory effects, underscoring the strong dependence of outcomes on wavelength, dose, exposure duration and crop or genotype.

UV radiation emerges as a significant regulatory factor in legume seed physiology and early growth, functioning both as a stressor and a signaling agent. Moderate UV exposure can act as a priming stimulus that breaks physical dormancy, accelerates germination, enhances metabolic activity and promotes early seedling vigor through adaptive physiological and molecular responses. In contrast, excessive or prolonged UV exposure overwhelms protective mechanisms, leading to oxidative damage, growth inhibition and reduced seed viability. The contrasting responses observed among legumes such as soybean, mung bean, Bengal gram and horse gram emphasize the importance of species- and genotype-specific sensitivity in determining UV tolerance and performance.

From an applied perspective, controlled use of UV radiation holds considerable promise in sustainable seed science and crop establishment. As a non-chemical, eco-friendly physical treatment, UV radiation can be exploited for seed invigoration, dormancy breaking and reduction of seed-borne pathogens, thereby contributing to improved crop stand establishment and resilience under changing climatic conditions. Future integration of UV treatment with modern seed technologies, supported by crop-specific dose optimization and molecular validation, may further enhance its utility in legume-based cropping systems. Overall, a deeper mechanistic understanding and judicious application of UV radiation can pave the way for innovative, sustainable approaches in legume seed technology and agricultural productivity.

REFERENCES

1. Alan H. Teramura, N.S. Murali, (1986). Intraspecific differences in growth and yield of soybean exposed to ultraviolet-B radiation under greenhouse and field conditions. *Environmental and Experimental Botany*, Volume 26, Issue 1, Pages 89-95, ISSN 0098-8472, [https://doi.org/10.1016/0098-8472\(86\)90057-2](https://doi.org/10.1016/0098-8472(86)90057-2).
2. Chamodi Gunathunga., Suraji Senanayake., Madhura Arunoda Jayasinghe., Charles Stephen Brennan., Tuyen Truong., Upul Marapana&Jayani chandrapala (2024). Germination effects on nutritional quality: A comprehensive review of selected cereals and pulses changes. *Journal of food composition and analysis*. Vol-128 <https://doi.org/10.1016/j.jfca.2024.106024>.

3. Chen, H., Chen, W., Li, C., & Guo, H. (2013). Intraspecific variation in UV-B tolerance and associated leaf traits in 19 soybean cultivars. *Plant Growth Regulation*, 70(2), 133–142. <https://doi.org/10.1007/s10725-013-9784-y>
4. De, A., Bhattacharyya, S., Nag, A., & Das, A. K. (2022). Effect of UV-C radiation on germination, antioxidant activity and phenolic content of mung bean (*Vigna radiata* L.). *Journal of Plant Growth Regulation*, 41(3), 1098–1111. <https://doi.org/10.1007/s00344-021-10358-1>
5. Falconi, C. J., Perez-Gilvez, A., Vergara-Yanez, V., & Cedeno-Loor, W. (2019). Effects of UV-C radiation on germination and seedling growth of Andean lupin (*Lupinus mutabilis* Sweet). *Industrial Crops and Products*, 127, 76–82. <https://doi.org/10.1016/j.indcrop.2018.10.075>
6. Foroughbakhch, R., Carrillo-Parra, A., Hernandez-Pinero, J. L., Hauad-Marroquin, L. A., & Sandoval-Rangel, A. (2019). Ultraviolet radiation effect on seed germination and seedling growth of common species from Northeastern Mexico. *Agronomy*, 9(5), 269. <https://doi.org/10.3390/agronomy9050269>
7. Gandhi, M., Bhatt, V., & Patel, K. (2019). Effect of UV-C radiation on seed germination, seedling growth and biochemical parameters of horse gram (*Macrotyloma uniflorum* Lam.). *International Journal of Plant Sciences*, 14(2), 155–163. <https://doi.org/10.15740/HAS/IJPS/14.2/155-163>
8. Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant Physiology and Biochemistry*, 48(12), 909–930. <https://doi.org/10.1016/j.plaphy.2010.08.016>
9. Ha P.T.T., Tran B. T. N., Tuyen T. P., Mason P., Henry R.J., Loi T. T. (2023). The Effects of UV Light and Methyl Salicylate on Phytochemical Constituents and Nutritional Traits in Common Bean (*Phaseolus vulgaris* L.) . *Legume Research*. 46(12): 1597-1603. doi: 10.18805/LRF-754.
10. Hernandez-Aguilar, C., Dominguez-Pacheco, A., Tenango, M. P., Valderrama-Bravo, C., Hernandez, M. S., Cruz-Orea, A., & Ordóñez-Miranda, J. (2021). Characterization of bean seeds, germination, and phenolic compounds of seedlings by UV-C radiation. *Journal of Plant Growth Regulation*, 40(2), 642–655. <https://doi.org/10.1007/s00344-020-10125-0>
11. International Seed Testing Association (ISTA). (2021). International Rules for Seed Testing. ISTA, Bassersdorf, Switzerland. <https://doi.org/10.15258/istarules.2021>
12. Jenkins, G. I. (2014). The UV-B photoreceptor UVR8: From structure to physiology. *The Plant Cell*, 26(1), 21–37. <https://doi.org/10.1105/tpc.113.119446>
13. Marcos-Filho, J. (2015). Seed vigor testing: An overview of the past, present and future perspective. *Scientia Agricola*, 72(4), 363–374. <https://doi.org/10.1590/0103-9016-2015-0007>
14. Babak Peykarestan., Mohammadreza Seify., Mohsen Shoukat Fadaei and Mohammad Hatim (2012). UV Irradiation Effects on Seed Germination and Growth, Protein Content, Peroxidase and Protease Activity in *Portulaca grandiflora* and *Portulaca oleracea*. *World Applied Sciences Journal* 17 (7): 802-808.
15. Rajendiran, K., Arulmozhi, D., & Sudaroli Sudha, J. (2013). Supplementary UV-B radiation induced oxidative stress and antioxidant defense in black gram (*Vigna mungo* L.). *Research Journal of Botany*, 8(1), 1–13. <https://doi.org/10.3923/rjb.2013.1.13>
16. Rajendiran, K., Thiruvasaran, K., & Vijayalakshmi, R. (2015). Influence of elevated ultraviolet-B radiation on growth, biomass, photosynthesis and antioxidant responses in green gram (*Vigna radiata* L.). *International Journal of Environmental Sciences*, 5(3), 62–76. <https://doi.org/10.6088/ijes.5030>
17. Sadeghianfar, P., Nazari, M., & Backes, G. (2019). Exposure to Ultraviolet (UV-C) Radiation Increases Germination Rate of Maize (*Zea mays* L.) and Sugar Beet (*Beta vulgaris*) Seeds. *Plants (Basel, Switzerland)*, 8(2), 49. <https://doi.org/10.3390/plants8020049>
18. Siddiqui, A., Dawar, S., Javed Zaki, M., & Hamid, N. (2011). Role of ultraviolet (UV-C) radiation in the control of root infecting fungi on groundnut and mung bean. *Pakistan Journal of Botany*, 43(4), 2221–2224.
19. Smykal, P., Vernoud, V., Blair, M. W., Soukup, A., & Thompson, R. D. (2014). The role of the testa during development and in establishment of dormancy of the legume seed. *Frontiers in plant science*, 5, 351. <https://doi.org/10.3389/fpls.2014.00351>
20. Upadhyay, Ankit & Kuiry, Braj & Ram, Bandi & Pani, Sai & Sr, Chormule & Kuiry, Mohan & Punia, Yash. (2020). Effect of UV radiation on seeds physiological parameter: A review. *Journal of Pharmacognosy and Phytochemistry*. 9. 1877-1879.
21. World Health Organization (WHO). (1979). Environmental Health Criteria 14: Ultraviolet Radiation. World Health Organization, Geneva, Switzerland. ISBN 9241540745.
22. Yang, Y., Zhang, L., Chen, P., Liang, T., Li, X., & Liu, H. (2020). UV-B photoreceptor UVR8 interacts with MYB73/MYB77 to regulate auxin responses and lateral root development. *EMBO Journal*, 39(2), e101928. <https://doi.org/10.15252/embj.2019101928>
23. Wen, Z., Lu, X., Wen, J., Wang, Z., & Chai, M. (2024). Physical Seed Dormancy in Legumes: Molecular Advances and Perspectives. *Plants (Basel, Switzerland)*, 13(11), 1473. <https://doi.org/10.3390/plants13111473>
24. Wu, Y., Shin & W.-S.(2026). Germination as a cost-effective processing strategy for enhancing industrial value of legume proteins, *LWT*, <https://doi.org/10.1016/j.lwt.2026.119487>.

legume seed coat- Cross section and UV penetration

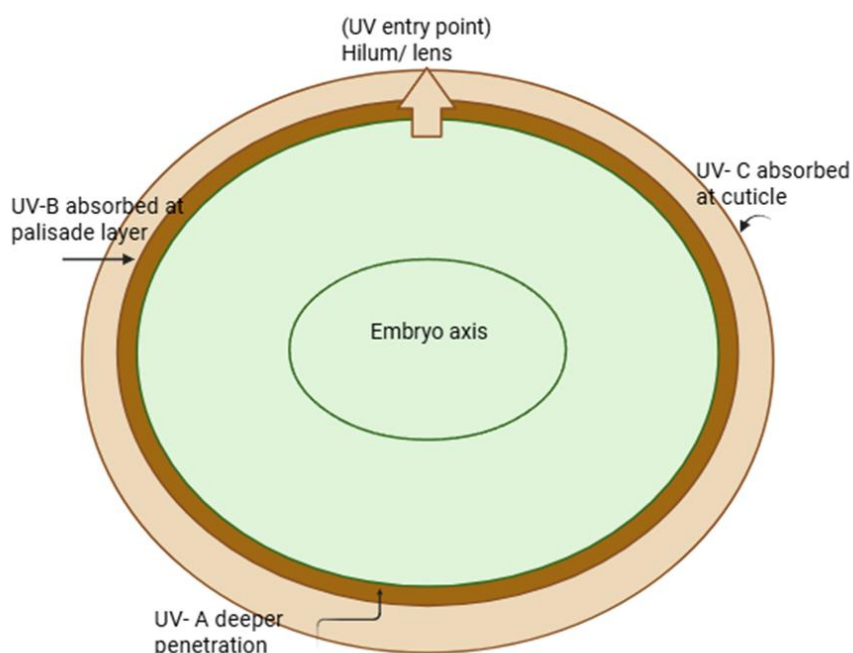


Figure 1: Structural characteristics of legume seed coats influencing UV response

Table 1: Sensitivity of Legume Seeds to Ultraviolet (UV) Radiation

Legume crop/ species	Seed coat structural features	Seed coat Pigmentation/phenolics	UV radiation on type studied	Observed Response to UV radiation	Physiological/ Biochemical reason	Key References
Soybean (<i>Glycine max</i>)	Thick testa; Well-Developed palisade layer; continuous cuticle	Moderate to high flavonoids & phenolics (cultivar dependent)	UV-B, UV-C	UV-B reduced seed size, yield; UV-C (low dose) improved germination	Thick seed coat limits penetration; UV-B alters ABA and cell division; phenolics act as UV screens	Teramura&Murali., 1986, Chen <i>et al.</i> , 2013., Hernandez-Augilar <i>etal.</i> , 2021

Mung bean (<i>Vigna radiata</i>)	Moderately thick seed coat; compact palisade cells	High inducible phenols and flavonoids	UV-B, UV-C	UV-C (short exposure) enhanced germination and vigour; UV-B induced phenolic accumulation	Seed coat restricts UV penetration; activation of phenylpropanoid pathway enhances protection	Rajendiran <i>et al.</i> , 2015; Sadeghianfar <i>et al.</i> , 2019; De <i>et al.</i> , 2022
Black gram (<i>Vigna mungo</i>)	Thick seed coat; strong palisade layer	High tannins and free phenols	UV-B	Increased phenols and tannins; moderate growth inhibition	Phenolic compounds absorb UV-B and scavenge ROS	Rajendiran <i>et al.</i> , 2013
Bengal gram (<i>Cicer arietinum</i>)	Hard seed coat; lignified palisade layer	Moderate phenolic content	UV-C	Improved germination and seedling growth at short exposure	UV-C modifies seed coat permeability without damaging embryo	Upadhyay <i>et al.</i> , 2020
Horse gram (<i>Macrotyloma uniflorum</i>)	Relatively thinner or less protective testa	Low to moderate phenolics	UV-C	Reduced germination, chlorophyll loss, growth inhibition	Lower antioxidant capacity; deeper UV penetration causes cellular damage	Gandhi <i>et al.</i> , 2019; Upadhyay <i>et al.</i> , 2020
Groundnut (<i>Arachis hypogaea</i>)	Thin seed coat; permeable testa	Moderate phenolics	UV-C	Enhanced seedling vigour and biomass at optimal dose	UV-C priming activates metabolism and reduces pathogens	Siddiqui <i>et al.</i> , 2011; Upadhyay <i>et al.</i> , 2020