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Research Article

Nano-Oxides and Phytohormones Mitigate Far-Red Light-Induced Inhibition of Seed Germination in Broccoli (*Brassica oleracea* var. *italica*)

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ABSTRACT

Light quality is a critical environmental factor regulating seed germination through phytochrome-mediated signaling pathways. This study investigated the effects of light wavelengths, nanoparticles, plant growth regulators, and photoreversible light treatments on the germination of broccoli (*Brassica oleracea* var. *italica*) seeds under controlled laboratory conditions. Broccoli seeds exhibited markedly higher germination (95%) in complete darkness than under continuous white light (41.6%), indicating a negatively photoblastic response. Among different light wavelengths, red light significantly enhanced germination (75%), whereas far-red light strongly inhibited germination (15%). Blue and UV light resulted in intermediate germination rates of 48.3% and 50%, respectively. Under inhibitory far-red conditions, MgO and Fe_2O_3 nanoparticles substantially improved germination, with maximum values of 95.0% and 96.3%, respectively, at 0.05 mg mL^{-1}. Higher concentrations reduced germination, suggesting concentration-dependent effects. Plant growth regulators also alleviated far-red-induced inhibition; gibberellic acid (GA_3) was the most effective treatment, achieving 95% germination at 100 and 150 ppm, while kinetin reached a maximum of 91.3% at 100 ppm. Germination responses were strongly influenced by the timing and sequence of dark and far-red exposures. Extended dark periods prior to far-red exposure partially mitigated inhibitory effects, whereas prolonged initial far-red exposure progressively reduced germination. Photoreversibility experiments demonstrated that a brief red-light exposure following far-red treatment increased germination from 68.0% to 88.3%, confirming the central role of phytochrome in regulating seed germination. In conclusion, broccoli seed germination is highly regulated by phytochrome-mediated light signaling. Red light, GA_3, and optimal concentrations of MgO and Fe_2O_3 nanoparticles effectively overcame far-red-induced inhibition and significantly enhanced germination.

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Introduction

Broccoli (*Brassica oleracea* L. var. *italica*) is an economically important vegetable crop of Brassicaceae family and is grown all over the world due to its remarkable nutritional and medicinal properties. The immature inflorescence and the edible part of the stem contain a high level of essential vitamins, minerals, dietary fiber and health-enhancing phytochemicals. In addition to high levels of vitamins A, C, and K, calcium, magnesium, potassium, and folates, broccoli is rich in biologically active compounds such as glucosinolates, sulforaphane, flavonoids, carotenoids, and selenium, which have proven to be potent antioxidants, anti-inflammatory and anticancer agents (Vallejo et al., 2004; Kumar and Srivastava, 2016; Astarini et al., 2020; Fahey et al., 2023). Due to these nutritive properties, broccoli is receiving greater interest as a functional food that has a wide range of health and disease prevention capabilities in humans.

Successful crop establishment relies on fast and uniform germination of seeds and subsequent plant growth, productivity and environmental stress tolerance. Germination of seeds and early development of seedlings, however, are very sensitive to external environmental conditions, especially availability of moisture, quality of light, temperature, and hormonal balance. The optimization of these factors is becoming more and more significant to improve the crop performance and the efficiency of resource use in protected cultivation and controlled environment agriculture. Therefore, there has been a growing focus on the use of innovative technologies that improve seed vigor and seedling establishment for modern crop production systems (Rouphael and Colla, 2020; Meena et al., 2022).

Light is one of the important environmental factors that affect germination. Apart from being a source of energy for photosynthesis, it is also a controlling factor for the growth and development of plants. Light is perceived by plants by its specific photoreceptors such as cryptochromes, phytochromes, and phototropins, which control seed germination, hypocotyl elongation, chloroplast development and photomorphogenesis. Red (600-700 nm) and far-red (700-800 nm) wavelengths are particularly important in regulating seed germination via phytochrome mediated signaling pathways. Germination responses and seedling establishment are affected by the balance of these wavelengths, which lead to the conversion of phytochrome between its inactive (Pr) and active (Pfr) forms (Paik and Huq, 2019; Liu and van Iersel, 2021). The knowledge gained from the effects of different light spectra on the germination of broccoli might be useful in developing better establishment protocols for controlled production systems.

Nanotechnology has become a potential technology for sustainable agriculture and crop protection in recent years. The application of nanoparticles, when used in appropriate concentrations, can increase the germination rate, uptake of nutrients, photosynthetic efficiency, antioxidant defense and tolerance to stress. Among these, silicon based nanoparticles have been of great interest due to their effects on improving seedling vigor, strengthening plant defense mechanisms, reducing oxidative stress and increasing tolerance to unfavorable environmental conditions (Schwab et al., 2016; Nagraj et al., 2020; Goswami et al., 2022; Naaz et al., 2023; Weisany et al., 2024; Yan et al., 2024). Nanotechnology can, therefore, be incorporated into seed treatment systems to provide novel solutions and opportunities to enhance crop establishment, yield and minimize reliance on traditional agrochemicals.

Plant growth regulators also have a significant effect on the regulation of germination of seeds and development of early seedling. Gibberellic acid (GA_3) has been one of the most extensively studied phytohormones that work in breaking seed dormancy, stimulating enzyme synthesis, mobilizing stored reserves, and stimulating cell elongation and growth. The exogenous use of GA_3 has been demonstrated to promote germination percentage, seedling growth and stress tolerance in various horticultural crops under both normal and stressed conditions (Nishiyama et al., 2011; Taiz et al., 2022, 2023). Thus, the synergistic effect of hormonal regulation along with optimum light conditions and nanomaterial application can be achieved *en route* to a better seed performance and better seedling quality.

The potential interactions among light spectral quality, nanomaterials and plant hormones is a new and intriguing line of research that can be applied to improve crop establishment in modern crop production systems. Even though various studies have investigated the individual effects of light quality, nanoparticles, or plant growth regulators on broccoli germination, there is little information available on the combined effects of these factors on seed germination and early seedling growth of broccoli. These holistic management strategies might play a crucial role in ensuring sustainable crop production under protected environments, improving seedling vigor and boosting their resistance to environmental stress.

The present study, therefore, aimed to evaluate the individual and synergistic effects of various light wavelengths, silicon nanoparticles, and GA_3 on the germination of seeds and early growth of broccoli seedlings under controlled environmental conditions for the development of useful strategies to enhance seedling establishment, vigor, and resistance to stress.

Materials and Methods

Experimental site

In 2025, a laboratory experiment was carried out at the Department of Biology, College of Science, Wasit University, Wasit, Iraq. The study investigated the effects of various wavelengths of light, plant growth regulators and nanoparticles on the germination of seeds and the growth of broccoli (*Brassica oleracea* var. *italica*). The experiments were conducted in a growth chamber in the Plant Graduate Studies Laboratory under controlled environment.

Seed material

The seeds of broccoli were collected from certified agricultural supply companies located in the Governorate of Wasit, Iraq. The seeds were bought and imported under commercial packaging from India. Seed viability was tested by standard germination tests, before the experiment, in order to achieve uniformity and high physiological quality. Seeds lots that showed high germination rates and normal seedling development were chosen for further experiments.

Seed sterilization and germination test

To prevent fungal contamination during germination, seeds were surface sterilized and treated with a commercial seed-treatment fungicide (House of Agri). The fungicide was sprayed uniformly over the surface of seeds and the seeds were air-dried on sterile gauze. Twenty seeds were then sown in each of 9-cm Petri dishes lined with sterile filter paper in three replicates per treatment.

The Petri dishes were put in a light-tight sealed box in order to guarantee total darkness. Further replicates were kept under light and dark to see if seed germination was light dependent or could take place in darkness. The sealed boxes and dishes that were exposed to light were then placed in a growth chamber (Environmental System, LabTech Daihan Labtech). Germination percentage was determined following incubation. The earlier studies showed that broccoli seeds showed germination mainly in the dark (Ibrahim and Sharhan, 2025).

Light treatments

LED light sources and optical filters were used to examine the germination of seeds under various wavelengths of light in a plant growth chamber. The experimental boxes made of wood, containing the Petri dishes, were placed into the chamber, and optical filters were used to let only certain wavelengths reach the seeds.

The following light treatments were used:

Red light (600-700 nm): Using a red optical filter, 414.5 μmol m^{-2} s^{-1} of red light was provided.

Far-red light (700-760 nm): Using a yellow and purple dual-layer filter, the irradiance for this light source was found to be 340.5 μmol m^{-2} s^{-1}.

Blue light (400-500 nm): A distinct blue optical filter was used to isolate the blue light.

White light (400-700 nm): The optical filters were removed and the seeds were directly exposed to the LED light source.

After the Petri dishes were placed inside the boxes, the filters were placed above the experimental units as required by treatments (Al-Ukaili, 1990).

Ultraviolet (UV-C) light treatment

The UV-C lamp was used as the radiation source and experiments were carried out on the UV radiation. A specially-designed ceramic chamber was built to provide stable experimental conditions. The chamber was set up with Petri dishes under the UV-C lamp and the seeds were added to these dishes. Petri dishes were placed inside the chamber, and the UV-C lamp was set at a fixed distance of 30 cm from the Petri dishes.

The UV-C treatment was performed under an intermittent regime with about 14 h of continuous UV-C irradiation, and 10 h of darkness per day, for 7 days, due to the local power supply conditions. The dark period allowed seeds to recuperate. On the other hand, red and far-red light treatments were provided throughout the 24 h day using rechargeable LED systems in order to avoid the dark recovery effects and to guarantee continuous exposure.

Preparation of hormone solutions

The solutions of GA_3 and kinetin (KIN) were prepared using the standard methods. In brief, 0.1 g of each hormone was weighed individually on an analytical balance, and dissolved in 1 mL of absolute ethanol to ensure that the hormones were completely dissolved. The solutions were then transferred to 100 mL volumetric flasks and made up to a volume of 1000 ppm of stock solution with sterile distilled water.

Four working solutions of 10, 50, 100, and 150 ppm were obtained by serial dilutions of the stock solutions with requisite amounts of sterile distilled water. All the solutions were kept in amber colored bottles at 4°C to maintain the stability and biological activity of the solutions (Sharhan et al., 2022).

Preparation of nanoparticle suspensions

This study was conducted with the help of iron oxide (Fe_2O_3) and magnesium oxide (MgO) nanoparticles. The certified purity of the nanoparticles was > 99% and the average particle size was 20-30 nm, confirmed by Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS) at the Department of Physics, College of Science.

Nanoparticle suspensions were prepared at the following concentrations: 0.01, 0.03, 0.05 and 0.07 mg mL^{-1}. The required amount of nanoparticle powder was firstly dispersed in 5 mL of ethanol to promote deagglomeration and stabilization. This suspension was then quantitatively transferred to a volumetric flask and diluted to 500 mL with the deionized water in a water bath with constant stirring to assure uniform dispersion. The fresh suspensions were then prepared just prior to application and 10 mL of each suspension was added to the corresponding treatment in Petri dish (Juma'a, 2025).

Determination of germination percentage

Two layers of filter paper were placed in 9-cm Petri dishes, and 20 seeds of broccoli were planted in each dish. Sufficient moisture was provided during the incubation period. Germination was determined after 7 days following International Seed Testing Association (ISTA) guidelines (ISTA, 2024).

The percentage of germination was determined by the following formula:

$$\text{Germination } (\%) = \frac{\text{No. of germinated seeds}}{\text{No. of seeds sown}} \times 100$$

Statistical analysis

The experiment was laid out in a Randomized Complete Block Design (RCBD). Percent germination data were analyzed using analysis of variance (ANOVA) by SPSS software version 29.0. Data were checked for normality using the Shapiro-Wilk test and the homogeneity of variance using Levene's test to ensure the parametric analysis assumptions were met prior to ANOVA. The Least Significant Difference (LSD) test was used to separate the treatment means at the 5% probability level ($P \leq 0.05$).

Results

Laboratory tests showed a significant difference between seed germination in the dark compared to light. When grown in complete darkness, the germination percentage of the broccoli seeds was high (95%), while continuous white light resulted in very low germination (41.6%) (Figure 1). This is a physiological response due to the activity of the phytochrome system which controls seed germination in response to light signals.

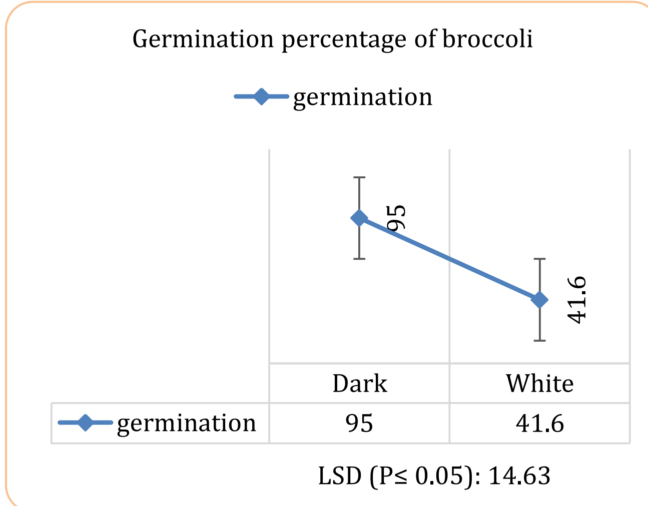

Figure 1. Germination percentage of broccoli seeds.

Seeds of broccoli seem to experience photodormancy after exposure to white light, which somehow inhibits the metabolic activities needed for mobilization of the reserves and embryo development. Darkness increases the sensitivity of tissues to gibberellins (GAs), the main hormones that break seed dormancy and stimulate hydrolytic enzymes, like α-amylase. This enzyme breaks down stored starch into soluble sugars which is used as a source of energy for the development of the embryo and emergence of radicle. On the other hand, extended exposure to white light might cause an increase or activity of abscisic acid (ABA), a plant hormone that inhibits germination. The observed decrease in germination in white light, therefore, indicates that under conditions of this experiment broccoli seeds are negatively photoblastic and have a maximum germination rate in the dark.

Figure 2 shows the effect of various light wavelengths on the germination of broccoli seeds, which revealed different physiological responses to light quality. Among the tested wavelengths, the highest germination percentage (75%) was observed with red light. This stimulatory effect might be explained by the conversion of phytochrome from the inactive form (Pr) to its biologically active form (Pfr) which stimulates gibberellin biosynthesis, prevents ABA-mediated inhibition, and activates genes related to germination. Far-red light, on the other hand, gave the minimum germination percentage of 15%. This is a natural response since far-red light reverts phytochrome to its inactive Pr form which would inhibit germination signals, thus promoting dormancy. The intermediate germination percentages were obtained for blue light (48.3%) and UV light (50%). The perception of blue light is largely mediated by cryptochromes and phototropins that control a number of developmental processes. Even though germination was found to be stimulated by blue light in some plant species, its effect on germination in broccoli was less noticeable as compared to red light, perhaps because of the interactions with the hormonal pathways involved in the inhibition of early embryo growth and cell division. Together, these results demonstrate the importance of the phytochrome system for controlling broccoli seed germination, red light being the most effective in promoting germination while far-red light the most effective in suppressing germination.

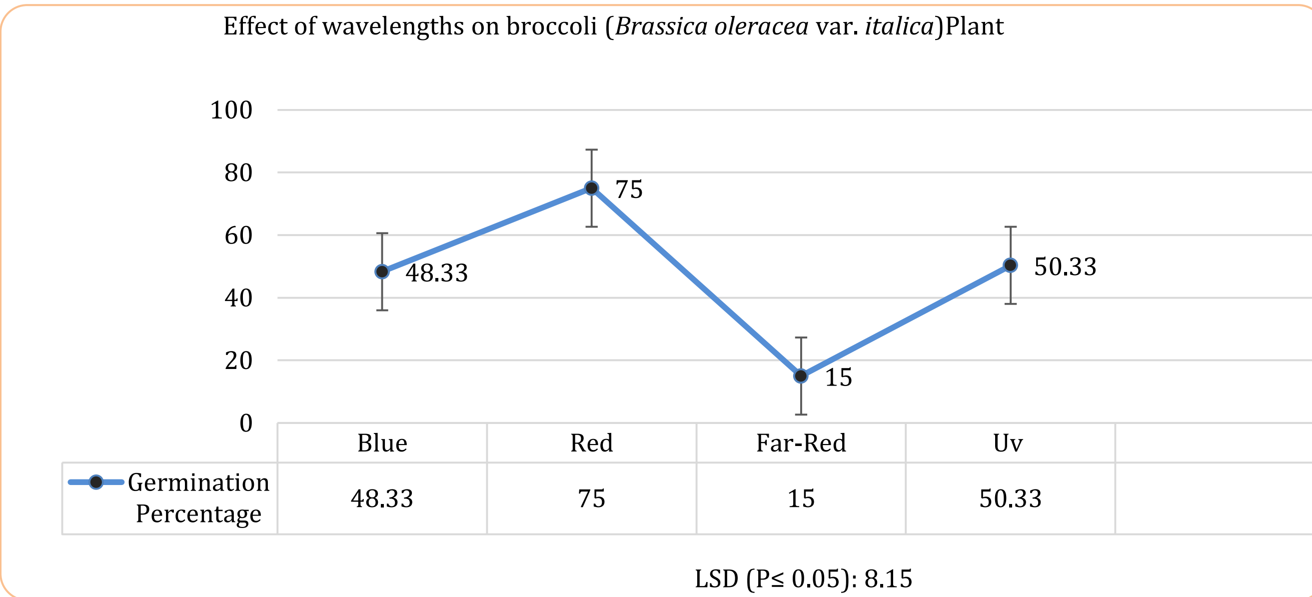

Figure 2. The effect of wavelengths on the germination percentage of broccoli seeds.

The data in Table 1 illustrate the effect of MgO and Fe_2O_3 nanoparticles on the germination of broccoli seeds in inhibitory far-red light. Both treatments with nanoparticles increased the germination compared to far-red control, which gave only 15.00% germination. MgO at the concentration of 0.01 mg mL^{-1} improved germination rate to 73.33% while Fe_2O_3 improved germination rate to 81.67%. The germination percentages with the application of MgO and Fe_2O_3 nanoparticles at the concentration to 0.03 mg mL^{-1} were 84.33% and 91.67%, respectively. The stimulatory effects were found to be the highest at 0.05 mg mL^{-1} concentrations of MgO and Fe_2O_3 showing germination percentages of 95.00 and 96.33, respectively.

On the other hand, when the concentration was increased to 0.07 mg mL^{-1}, MgO reduced the germination to 81.67% while Fe_2O_3 to 80.00%. This decrease indicates that there exists an optimal threshold concentration after which the beneficial effects begin to decrease, possibly as a result of physiological stress or toxicity caused by the nanoparticles. All treatments with nanoparticles showed significantly better germination results than the far-red treatment based on the LSD values (12.20 for MgO and 11.50 for Fe_2O_3), demonstrating that these treatments under inhibitory light conditions have potent promoting effects.

Table 1. Effect of nanoparticles on the germination percentage of broccoli seeds.

Treatments	MgO Nanoparticles	Fe_2O_3 Nanoparticles
6 Day Far-red	15.00	15.00
0.01	73.33	81.67
0.03	84.33	91.67
0.05	95.00	96.33
0.07	81.67	80.00
LSD ($P \le 0.05$)	12.20	11.50

Table 2 showed that gibberellic acid and kinetin were the most effective plant growth regulators in stimulating germination of broccoli seeds under far-red light conditions. The gibberellic acid at 100 ppm and 150 ppm gave the highest germination percentage of 95.00%. This stimulatory activity is thought to be due to its key function in the activation of hydrolytic enzymes, especially α-amylase, that release stored reserves to support the growth of the embryo. In addition, the effect of exogenous application of GA_3 can overcome the dormancy period by triggering the expression of germination-related genes under far-red light conditions, which results in the lack of Pfr (active phytochrome) in the plants.

Table 2. Effect of plant hormones (ppm) on the germination percentage of broccoli seeds.

Treatments	GA3	Kinetin
6 Day far-red control	15.00	15.00
10	88.67	81.67
50	93.33	86.67
100	95.00	91.33
150	95.00	73.67
LSD ($P \leq 0.05$)	8.46	9.50

Kinetin also showed considerable stimulatory effect with the highest germination rate of 91.33% at 100 ppm. However, when the concentration was increased to 150 ppm, germination declined to 73.67%. This decrease could be due to hormonal imbalance or to possible mild phytotoxic effects caused by the high level of cytokinin that can retard the elongation of the radicle and interfere with normal developmental processes. All the hormonal treatments used were significantly different from the control, suggesting that the seeds of broccoli were very sensitive to the growth regulators when placed under suboptimal light conditions (LSD = 0.05). As a whole, GA_3 was the most effective and consistent treatment, retaining high germination rates at all concentrations and outperformed kinetin at high concentrations.

The interaction of darkness and far-red light on the germination of seeds of broccoli is shown in Table 3. Two control treatments were also tested: 6 days of continuous darkness resulted in 95% germination and 6 days of continuous far-red light resulted in 15% germination. The results of the combined treatments clearly showed that the germination responses were highly sensitive to the timing and sequence of the exposure, rather than to the additive effect of the two exposures. The treatments of 1 day of far-red light combined with different dark periods resulted in germination percentages of 55.00 to 71.67, significantly less than the darkness treatment, but significantly more than the far-red treatment (LSD value 12.16). The best germination rate of 71.67% was obtained under the mixed treatments, with far-red light being applied on the last day after five days of darkness. Intermediate germination of 65.00% was achieved with far-red light when applied between dark periods while the lowest germination (55.00%) was achieved when far-red light was given in the early part of the treatment. The results show that extended dark exposure before far-red light exposure somewhat reduces the inhibitory effect of far-red light on subsequent germination, while early exposure to far-red light has a greater inhibitory effect on subsequent germination. The statistical analysis did not detect significant differences between the germination percentages of 71.67 and 65.00 and among the lower three values of 58.33%, 58.00% and 55.00%. The highest value, however, was quite different from the lowest group. Not surprisingly, all the treatments had a lower germination percentage than the darkness control, and the far-red control had the lowest germination percentage.

Table 3. Effect of far-red light at different exposure periods on germination percentage of broccoli seeds.

Treatments	% germination
6D	95.00
6 FR	15.00
5D - 1FR	71.67
4D - 1FR - 1D	65.00
3D - 1FR - 2D	58.33
2 D - 1FR - 3 D	58.00
1 D - 1FR- 4 D	55.00
LSD ($P \leq 0.05$)	12.16

Note: D = Days of complete darkness; FR = Days of continuous far-red light exposure.

Figure 3 shows the effect of the duration of the initial far-red light exposure on broccoli seed germination. A negative correlation between the length of far-red exposure and final germination percentage was found. After two days of far-red light and 4 days of darkness

(2FR-4D), 80.00% seeds germinated showing a considerable recovery from the inhibitory effects of far red light after transfer to darkness. Four days of far-red light followed by two days of darkness (4FR-2D) however, resulted in a significant decrease in germination to 70.00%. This reduction was statistically significant as indicated by the LSD value (9.41). Prolonged maintenance of phytochrome in the inactive Pr form during early germination stages appears to enhance the chances of secondary dormancy, thus limiting subsequent ability of seeds to respond to favorable conditions.

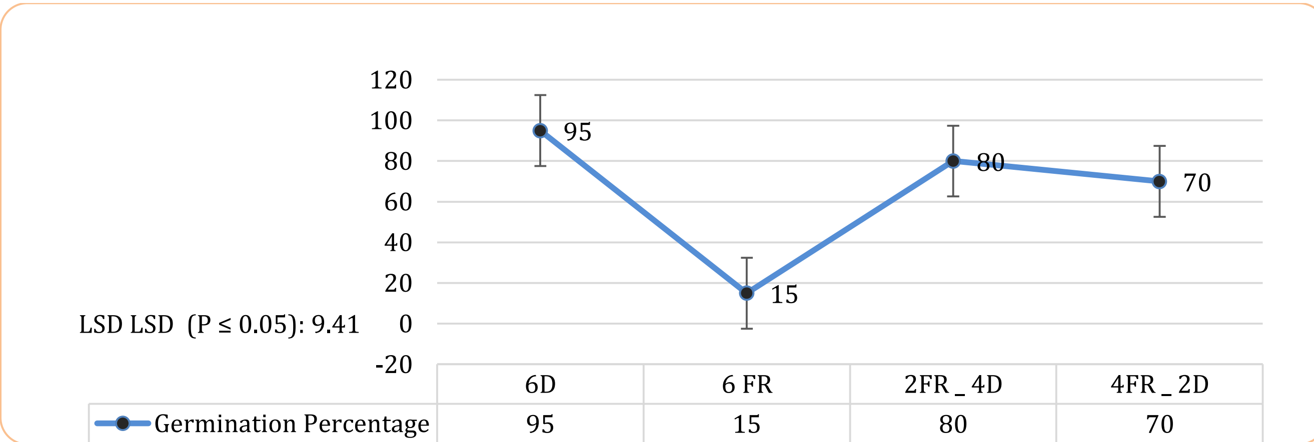

Figure 3. Effect of far-red light at different exposure periods on germination of broccoli seeds.

The results in Table 4 are clear proof of the photoreversibility of the germination of broccoli seeds caused by phytochrome. The results indicate that the light signal received by the seeds at their final stage of development is a key determinant of their germination. The germination was 68.00% when the last exposure was far-red. However, a short (10 min) exposure to red light following far-red light treatment had a dramatic effect, boosting germination to 88.33%, nearly equal to the complete dark treatment (95.00%). The shift from Pfr to Pfr induced by exposure to red light may account for this response. Active phytochrome induces gibberellin biosynthesis and/or metabolism pathways related to germination, which counteracts the inhibition caused by far-red light. These short light treatments caused significant differences in germination percentage with the LSD value being 9.35. The results presented here are strong evidence that phytochrome-mediated control of broccoli seed germination is reversible and highlight the importance of the last light environment on germination.

Discussion

The differential germination responses of broccoli seeds to various light wavelengths can be attributed to the sensitivity of the phytochrome system, particularly phytochromes A (PhyA) and B (PhyB). Red light (approximately 660 nm) converts phytochrome to its biologically active form (Pfr), which translocates to the nucleus and interacts with phytochrome-interacting factors (PIFs), thereby relieving transcriptional repression and activating genes associated with dormancy release and germination. These include genes encoding cell wall-loosening proteins, such as expansins, and hydrolytic enzymes involved in reserve mobilization. On the other hand, far-red light (approximately 730 nm) converts Pfr back to its inactive Pr form, suppressing metabolic processes required for embryo growth and radicle emergence, resulting in a marked reduction in germination (Liu et al., 2022; Santini et al., 2023).

The promotive effects of plant growth regulators on seeds exposed to inhibitory far-red light are primarily associated with hormonal regulation of germination. Gibberellic acid acts as a physiological switch that can bypass the requirement for light-mediated phytochrome activation by stimulating the synthesis of hydrolytic enzymes and promoting embryo growth (Oka et al., 2025). The present results demonstrated that both GA_3 and kinetin significantly enhanced broccoli seed germination under far-red light conditions, effectively compensating for the absence of active phytochrome signaling. Similar findings were reported by El-Rasafi

(2025), who showed that GA promotes germination in light-sensitive seeds even under far-red illumination. On the contrary, prolonged far-red exposure suppresses germination by maintaining phytochrome in its inactive state, reducing endogenous gibberellin levels while increasing abscisic acid accumulation, thereby reinforcing dormancy (Al-Ukaili, 1990).

Table 4. Effect of the interaction between far-red and red light on the germination percentage of broccoli seeds.

Treatments	% germination
6D	95.00
6 FR	15.00
4 D - 1F - D	65.33
4 D - 1FR - 5 min Red - D	75.00
4 D-1FR -10 min Red -D	71.33
4 D-1FR - 10 min Red - 10 min FR	68.00
4 D -1FR - 10 min Red - 10 min FR -	88.33
LSD ($P \leq 0.05$)	9.35

Note: D = Days of darkness; FR = Far-red light; R = Red light; min = Minutes of exposure duration.

Nanoparticle treatments improved seed germination through multiple physiological mechanisms. Nanoparticles may enhance seed coat permeability to water and oxygen, facilitate nutrient uptake, and induce a mild oxidative burst that serves as a hormetic signal, stimulating antioxidant defense systems such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX). These responses promote cellular metabolism and support radicle protrusion. Moreover, nanoparticles may act as catalytic agents that accelerate enzymatic activities and modulate endogenous hormone levels, including auxin (IAA), thereby facilitating seedling establishment under suboptimal environmental conditions (Koelmel et al., 2013; Tawfik et al., 2021; Yousuf et al., 2025).

The photoreversibility experiments further confirmed the central role of phytochrome in regulating broccoli seed germination. Germination responses were strongly influenced by the sequence and duration of light treatments, indicating that the physiological outcome depends largely on the final Pfr/Pr ratio. Far-red light decreases the proportion of active phytochrome (Pfr), whereas red light restores it. During prolonged dark periods, partial recovery of germination may occur through dark reversion processes and hormonal adjustments that favor gibberellin biosynthesis and reduce ABA-mediated inhibition. As a result, the inhibitory effects of far-red light were alleviated when sufficient dark intervals were introduced or when far-red exposure was followed by red light treatment (Rizza and Jones, 2019; Al-Jaafari and Al-Zurfi, 2024; Azizi et al., 2025).

The superior germination and growth observed under darkness can also be explained by etiolation, a developmental strategy characterized by enhanced elongation of the radicle and plumule. This response is mediated by increased auxin activity, greater cell wall extensibility, and the allocation of seed reserves toward rapid elongation, enabling seedlings to reach favorable light conditions (Taiz et al., 2015; Sharhan et al., 2022). In contrast, exposure to light initiates photomorphogenesis, whereby photoreceptors such as phytochromes and cryptochromes regulate gene expression, suppress excessive elongation growth, and promote tissue differentiation and chloroplast development (Kami et al., 2010). Although red light stimulated germination through phytochrome activation, blue and far-red wavelengths exerted comparatively inhibitory effects due to their influence on hormonal balance and light-signaling pathways (Feizi et al., 2013; Ali et al., 2020).

Conclusions

The results of the present study showed that the quality of light plays an important role in the germination of broccoli seeds, with a strong influence on the phytochrome-mediated signaling pathways. Red light stimulated germination by activating phytochrome and stimulating germination-related metabolic and hormonal processes while far-red light strongly inhibited germination by keeping phytochrome in its inactive state and by reinforcing dormancy. The various photoreversible responses to alternating red and far-red light treatments provided additional evidence of the key role of phytochrome in germination control.

The application of MgO and Fe_2O_3 nanoparticles along with plant growth regulators viz. GA_3 and kinetin proved to be effective in reducing the adverse effect of far-red and significantly improved germination. Optimal concentrations of nanoparticles, and the use of GA_3, showed the highest promotive effects among the treatments tested. The results show the possibilities of combining light management with nanotechnology and plant growth regulators for better seed germination, establishment of seedlings and better crop production. These methods can offer useful resources to improve propagation practices and agricultural production systems.

Author Contributions

OAA conceived and conducted the experimental work, collected and analyzed the data, and prepared the initial manuscript draft. MHS supervised the study, contributed to the development of the research concept and title, and guided the design of the methodology and experimental workflow. Both authors reviewed, revised, and approved the final version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 2: Zero Hunger
SDG 3: Good Health and Well-Being
SDG 12: Responsible Consumption and Production

Policy Addressed

This research supports policies related to sustainable agriculture, food and nutritional security, climate-smart crop production, agricultural innovation, nanotechnology applications, and seed quality enhancement through the development of environmentally friendly approaches for improving broccoli seed germination and establishment.

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