

Growth of mustard with reference to Nanomaterials under Insect-Induced Stress by Mustard Aphid (*Lipaphis erysimi*)

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Abstract—Mustard (*Brassica juncea* L.) is one of the major oil seed crops of which production suffers negatively because of insect-imposed stresses especially the mustard aphid (*Lipaphis erysimi*). Such biotic stress needs to be reduced by sustainable methods, and the reliance of non-sustainable agrochemical methods is reduced. The aim of the study was to assess the potential of the selected nanomaterials in reducing the effect of aphids and enhancing the growth, physiological and biochemical performance of the mustard plant. The experimental design used was controlled with four treatment groups including control, aphid-infested untreated plants, nanomaterial-treated non-infested plants, and nanomaterial-treated aphid-infested plants. The analysis was performed on growth parameters, chlorophyll content, biochemical constituents, and antioxidant activity, and the statistical evaluation of the data was done by ANOVA. Aphid infestation greatly lowered seed germination, plant height, the number of leaves, biomass, chlorophyll, and chlorophyll content, and metabolic constituents. The use of nanomaterials was found to boost the growth and preserve photosynthetic pigments, as well as increase protein, carbohydrate, and antioxidant concentrations in normal and aphid-stress conditions. The effects of the treatment were statistically significant ($p < 0.05$). The use of nanomaterials was effective to reduce stress caused by the aphid and enhance the growth and metabolic stability of *Brassica juncea*. The results indicate that nanomaterials can be an effective and sustainable approach to the management of insect stress in mustard farming.

Index Terms—*Brassica juncea*, nanomaterials, mustard aphid, biotic stress, growth performance

I. INTRODUCTION

Mustard (*Brassica juncea* L.) is a large oil seed crop in India and contributes greatly to the enhancement of the agricultural economy as well as to the need of the edible oil [1]. The efficiency of seed germination and the adequate working of biochemical and metabolic processes during the initial stages of the plant development have a strong impact on the crop growth and yield [2]. Any form of disturbance at this stage has a negative influence on crop establishment and end productivity. Insect infestation, especially by mustard aphid (*Lipaphis erysimi*) and painted bug (*Bagrada hilaris*) is one of the most severe biotic constraints, which reduces the germination rate, metabolic imbalance, and yield reduction in mustard. Nanotechnology has recently attracted significant interest in agricultural sciences in terms of enhancing plant growth, metabolism and resistance to biotic stress, and can be viewed as a promising strategy [3]. Nanomaterials (NMs), i.e., iron oxide nanoparticles (Fe₂O₃-NPs), zinc oxide nanoparticles (ZnO-NPs), and silver nanoparticles (AgNPs) are rapidly becoming considered as nutrient delivery agents, seed priming agents, as well as plant protectants [4]. These nano materials present new ways of improving crop performance and minimise the use of traditional agrochemicals.

The latest developments in the agricultural nanotechnology have found the nanomaterials as useful agents to enhance the performance and stress resistance of crops [5]. Nanomaterials have a high surface area, high reactivity, and better bioavailability due to their nanoscale size thus interacting effectively with plant tissues and cellular systems. They have

been reported to enhance seed germination, nutrient uptake, enzyme activation and antioxidant defense against oxidation in plants [6]. Mustard (*Brassica juncea* L.) is a valuable crop in sustainable farming as it is a popular crop mostly grown with oil in its seeds. The initial germination of seeds and the establishment of seedlings are important factors that define the vigor of plants and yield [7]. Nevertheless, these initial development phases are highly susceptible to attacks by insects and in particular sap-sucking insects like the *Lipaphis erysimi* and tissue-feeding insects like *Bagrada hilaris* which cause oxidative stress and interfere with normal physiological and biochemical processes [8]. Although there is growing interest in the use of nanomaterials in agricultural practices, little research has focused on the interaction between nanomaterials and the stress inflicted on insects by the key mustard pests [9]. To identify the viability of nanomaterials in improving crop tolerance and crop productivity, the infested mustard plants with *Lipaphis erysimi* and *Bagrada hilaris* should be evaluated comparatively under the treatment of nanomaterials and without it [10]. Thus, the current research is expected to determine the efficiency of nanomaterials in reducing insect-induced stress and the effect of nanomaterials on seed germination and biochemical values of *Brassica juncea* in the presence of pests [11].

1.1 Nanotechnology in Agriculture: Concept and Role in Enhancing Plant Growth

Nanotechnology has become a prospective development in contemporary agriculture, because of the special physicochemical characteristics of nanomaterials, such as a great surface area, higher reactivity, and better solubility [12]. Nanomaterials are also finding application in agriculture as nano-fertilizers and nano-nutrients to enhance the delivery and uptake of nutrients by the plants [13]. Nano size of most of these essential elements including zinc, iron, silicon and nitrogen when applied has been reported to increase photosynthetic activity, chlorophyll synthesis, enzyme activation and root growth [14]. The properties enable nanomaterials to engage effectively with plant physiological mechanisms to achieve better growth and biomass buildup using less input [15].

1.2 Nanomaterials and Mitigation of Insect-Induced Stress

The infestation of plants with *Lipaphis erysimi* and *Bagrada hilaris* has a drastic impact on the physiology, metabolism, and yield of plants by causing the oxidative stress and changes in the major biochemical processes [16]. Recent research in agricultural nanotechnology indicates that nanomaterials can be a useful means of alleviating crop stress due to insects. Nanomaterials are effective in their interaction with plant tissues due to their nanoscale size, large surface area, and high reactivity and can influence insect feeding behavior indirectly [17]. Nanomaterials increase the levels of chlorophyll, antioxidant enzyme activity, and metabolism of carbohydrates and proteins in response to insect attack, which improves the physiological performance of plants.

Moreover, some nanomaterials are insecticidal or repulsive to insects, and this property can potentially decrease the level of mustard aphids and painted bugs infestations [18]. Therefore, nanomaterials can be used to offer alternative pesticides to traditional ones, which are environmentally unfriendly, by enhancing plant defense systems and decreasing physiological losses inflicted by insect pests [19]. The application of nanomaterials in a judicious way can help to enhance crop yield, facilitate sustainable agriculture, and facilitate integrated pest management practices in the production of mustard [20].

Aim

To evaluate the effect of selected nanomaterials on the growth and physiological performance of mustard (*Brassica juncea* L.) under insect-induced stress caused by mustard aphid (*Lipaphis erysimi*).pro

Objectives

- I. To assess the effect of nanomaterials on growth parameters of mustard (*Brassica juncea* L.) under normal conditions.
- II. To evaluate the impact of mustard aphid (*Lipaphis erysimi*) infestation on growth and physiological parameters of mustard plants.
- III. To study the role of nanomaterials in mitigating aphid-induced stress and improving growth performance of mustard plants.

II. REVIEW OF LITERATURE

Varadharajan et al., (2025) studied Plants are subjected to many abiotic and biotic stresses which have negative impact on growth and crop productivity. The abiotic stresses like extreme temperatures, drought, salinity, flood, UV radiation and heavy metal toxicity disturb the physiological and metabolic mechanisms and the biotic stresses, caused by insects and pathogens, only cause further damages to the plant systems. These stresses occur at both molecular, cellular and developmental level and plant responses are very complicated. Recent reviews demonstrate the significance of multi-omics techniques, which combine genomics, proteomics, metabolomics, ionomics, and phenomics, to have a more comprehensive view of regulatory network responses to stress. The integration of these strategies assists in determining major stress tolerance processes and in constructing the enhanced crop resilience via breeding, genetic engineering, and genome-editing methods [21].

Nazeer et al., (2025) concluded that Insect infestation is one of the greatest limitations of agriculture, which negatively influences the growth of plants and economic productivity and especially in regions that rely on agriculture. Research has shown that plant growth-promoting rhizobacteria (PGPR) can be used as alternatives to chemical pesticides and fertilizers because they improve the host defences of plants. Third-generation insecticides like lufenuron are insect growth regulators (IGR) that prevent pest infestation by blocking the synthesis of chitin and interrupt insect growth. Experiments conducted in the fields with cauliflowers have indicated that foliar application of lufenuron is effective in decreasing the population of the pests such as cutworms, diamondback moths, armyworms, and aphids. Also, the inoculation with PGR makes plants more resistant, as it boosts phenols, proline, and antioxidants enzymes, making them more tolerant to the oxidative stress caused by insects [22].

Francis et al., (2024) acknowledged that nanomaterials have the capability to modulate physiological and biochemical responses in plants subjected to insect-induced stress, integrating nanotechnology with plant stress management. Plants treated with nanomaterials exhibited improved chlorophyll retention, enhanced antioxidant defense,

and maintenance of metabolic homeostasis under aphid pressure. The results of these tests indicate that nanomaterials have significant potential to improve the growth and resilience of mustard plants under stress from mustard aphid infestations [23].

Xia et al., (2023) studied Cruciferous plants produce glucosinolates (GSLs) as major defense molecules against insect herbivores, but the control of such a response in response to feeding is complicated. Investigations of mustard (*Brassica juncea*), which is in contact with beet armyworm (*Spodoptera exigua*) indicate that GSL accumulation is highly stimulated by insect feeding after 48 hours which is mainly composed of sinigrin. The transcriptome analysis showed a massive enrichment of differentially expressed genes especially in glucosinolate and jasmonic acid (JA) synthesis pathways. Herbivory induces JA signalling to stimulate production of GSL and, at the same time, controls JA catabolism, and activators and repressors of signalling. Such a controlled regulation can be used to protect insects efficiently and avoid overgrowth repression in mustard plants [24].

DEY et al., (2023) Examined the concept that the growth regulator SA may augment the protection of the photosynthetic machinery by upregulating morphological features in these plants. The experimental design included planting mustard seeds in a field under natural environmental conditions. At the 15-day development stage, the plants had various amounts of TU and SA treatments for a duration of 3 days. Thereafter, they were let to develop for a duration of 90 days. Numerous morphological characteristics were rigorously assessed in the upright mustard plants. After the application of SA and TU, significant enhancements were seen in the quantity of nodes, main branches, leaf area, and internodal length of the plants. The findings indicated that the morphological features of the mustard plants were upregulated by the application of SA and TU. Moreover, after the application of these compounds, a comprehensive examination of the modifications in functional groups inside the leaves was performed [25].

Mazumder et al., (2020) evaluated studies related to the development of nanomaterials in crop production and found out that nano-based inputs like ZOX and IOO nanoparticles are beneficial additives in enhancing parameters of growth in mustard in terms

of plant height, leaf area, chlorophyll content and biomass in optimum dosage. Enhanced nutrient uptake efficiency, improved antioxidant enzymes activity, and improved metabolic balance were cited as some of the major mechanisms by which the nanomaterials enhance the growth of plants. These gains in the vigor of plants are said to indirectly increase tolerance to biotic stresses such as aphid infestation [26].

Sharma et al., (2020) determined the impact of phosphorus solubilizing bacteria (PSB) and vesicular-arbuscular mycorrhiza (VAM) and their joints on oxidative stress response in *Brassica juncea* under the herbivory of *Spodoptera litura*. The antioxidant enzymes that were examined included six viz. superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), monodehydroascorbate reductase and glutathione reductase (GR). findings showed that there was a random upsurge of APX and GR in PSB-enriched plants. Conversely, VAM- supplemented plants exhibited an active systemic defence response towards herbivory with the growth of all the six enzymes at 72 h. On the other hand, the concomitant supplementation of PSB-VAM resulted in the elevation of APX, SOD, CAT and POD enzyme, which died away by 72 h. Therefore, VAM as an independent or combined factor with PSB was somehow a vaccine to plants against stress. Nevertheless, the temporal dynamics of antioxidants were controlled by mode of action of PSB and VAM. Our experiment, therefore, demonstrates that microbial fertilizers also exert conspicuous impacts on the immunity of plants [27].

III. METHODOLOGY

3.1 Experimental Design and Study Site

The present study was conducted under controlled experimental conditions to evaluate the effect of selected nanomaterials on the growth and physiological performance of mustard (*Brassica juncea* L.) under insect-induced stress caused by mustard aphid (*Lipaphis erysimi*). A completely randomized design (CRD) was followed with appropriate replications to ensure statistical validity. The experiment was conducted in the rabi season with natural photoperiod and temperature conditions which were favorable to grow mustard.

3.2 Plant Material and Seed Preparation

Healthy seeds of *Brassica juncea* L. were certified and obtained at a reputable agricultural supplier of seeds. Before sowing, surface sterilization was done with 0.1% mercuric chloride during 1-2 minutes after which the seeds were washed in distilled water to eliminate all traces of the disinfectant. This measure guaranteed the removal of pathogens on the surface, as well as even germination.

3.3 Preparation and Application of Nanomaterials

In this study, the selected nanomaterials included zinc oxide nanoparticles (ZnO-NPs), iron oxide nanoparticles (Fe₂O₃-NPs), and silver nanoparticles (AgNPs), due to the reported importance of these nanomaterials in the growth and tolerance of plants to stress. Stock solutions of all nanomaterials were made using distilled water at a specific concentration depending on previous standardized experiments. The suspensions of the nanoparticles were sonicated to achieve a consistent level of dispersion prior to use. The application of nanomaterials was done at the seedling level through the spray of a hand sprayer until a steady coating was attained by uniform wetland of the leaves.

3.4 Aphid Infestation and Stress Induction

The infestation of mustard aphid (*Lipaphis erysimi*) was naturalized by placing plants in an environment with the presence of aphids or by manipulating the aphids to be on test plants. Aphid population was also left to develop and increase to form biotic stress condition. Aphid infestation of both treated and untreated nanomaterial plants was done to monitor the relative mitigation effect of nanomaterials upon stress.

3.5 Treatment Groups

The experimental setup consisted of the following treatment groups:

- Control (untreated, non-infested plants)
- Aphid-infested plants without nanomaterial treatment
- Nanomaterial-treated plants without aphid infestation
- Nanomaterial-treated plants under aphid infestation

Each treatment was replicated to maintain experimental reliability.

IV. RESULT

3.6 Assessment of Growth Parameters

The following parameters of growth, namely, the percentage of germination, plant height, the number of leaves, and the biomass accumulation, were measured at specified time intervals. These parameters were employed to determine the level of plant Vigor and general growth performance in both normal and stress conditions.

3.7 Physiological and Biochemical Analysis

Standard spectrophotometric techniques were used to estimate such physiological parameters as chlorophyll content. To ascertain the metabolic response of the mustard plants to aphid stress and the nanomaterial treatment, biochemical analysis was conducted through the determination of total protein, carbohydrate content and antioxidant enzyme activity in the samples in accordance with the protocols.

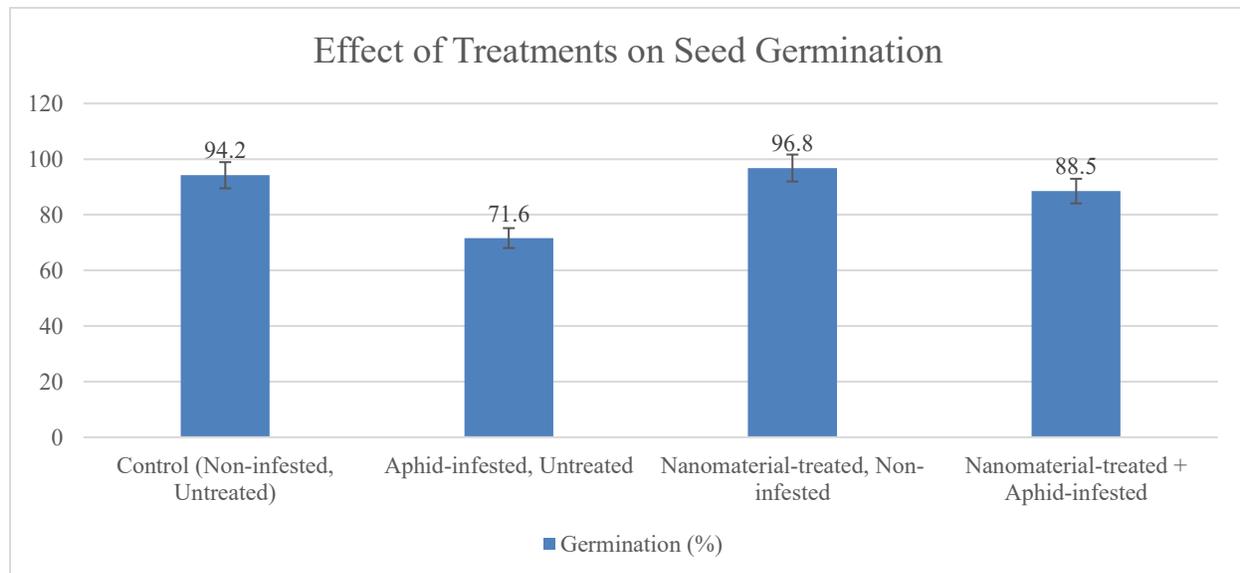
3.8 Statistical Analysis

Statistical analysis of the data collected was done using the right statistical tools. The mean values and standard deviations were obtained, and analysis of variance (ANOVA) was done to find the level of significance of differences between the treatments. A statistically significant result was taken at $p < 0.05$.

Table 1. Effect of Nanomaterials and Aphid Infestation on Seed Germination of Brassica juncea

Treatment	Germination (%)
Control (Non-infested, Untreated)	94.2 ± 2.1
Aphid-infested, Untreated	71.6 ± 3.4
Nanomaterial-treated, Non-infested	96.8 ± 1.8
Nanomaterial-treated + Aphid-infested	88.5 ± 2.6

Interpretation: Table 1 illustrates the effect of nanomaterials and aphid on seed germination of *Brassica juncea*. The control treatment had high germination which shows good conditions of viability of the seed. Aphids led to a significant reduction in the percentage of germination, which indicated adverse effects of the stress of insects on the initial plant establishment. Conversely, the seed germination of nanomaterial-treated seeds was better when there was no infestation, and it was a sign of seed Vigor. Notably, application of nanomaterials in aphid-infested conditions had a significant effect of restoring germination as compared to untreated infested plants, which implies that nanomaterials have the potential to alleviate aphid-induced stress conditions and enhance germination performance in mustard.



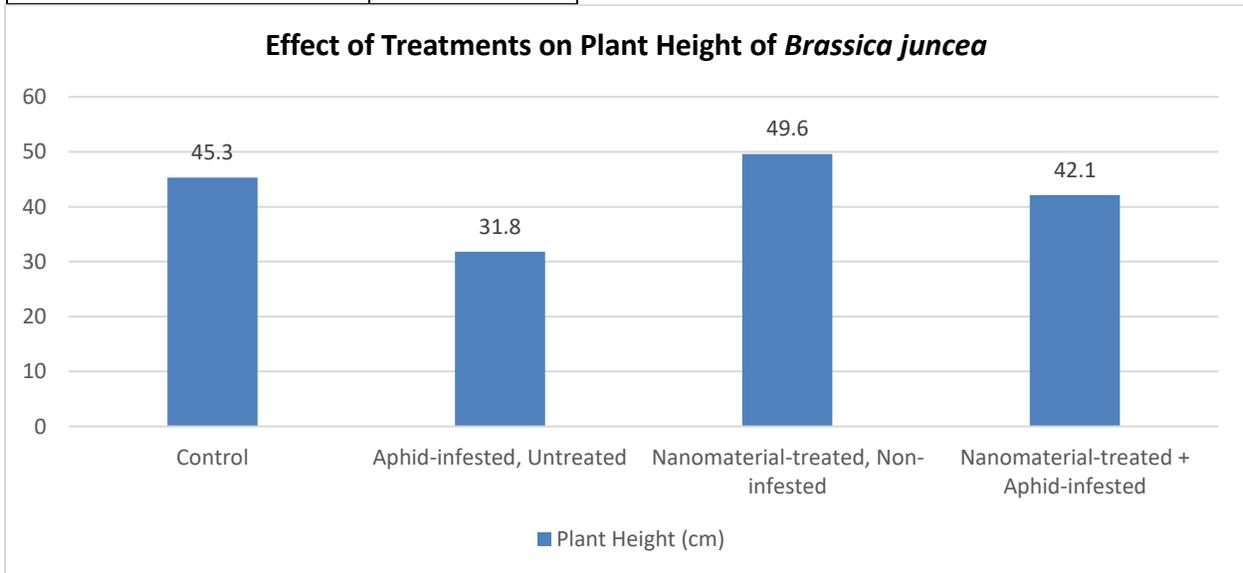
Graph 1: Effect of Treatments on Seed Germination

Graph 1 indicates that the infestation of aphids drastically decreased seed germination of *Brassica juncea* and nanomaterial treatment increased seed germination in normal and stressed environments. The higher germination of nanomaterial-treated aphid-infested plants suggests that they are useful in reducing the stress caused by insects and improving the germination of seeds.

Table 2. Effect of Treatments on Plant Height of Mustard

Treatment	Plant Height (cm)
Control	45.3 ± 2.5
Aphid-infested, Untreated	31.8 ± 2.1
Nanomaterial-treated, Non-infested	49.6 ± 2.8
Nanomaterial-treated + Aphid-infested	42.1 ± 2.4

Interpretation: Table 2 indicates that the height of the plant of mustard was significantly lower in aphid infestation than in the control, which was an indicator of high growth inhibition by insect stress. The height of the plants treated with nanomaterials was maximized in the non-infested environment, which indicates that nanomaterials promote growth in plants. Notably, when nanomaterials were used during aphid infestation, the height of plants was significantly enhanced relative to infested plants without the nanomaterial, which significantly indicated that nanomaterials could help reduce aphid-induced growth inhibition. In general, the findings denote that nanomaterials improve vegetative growth and are effective in supporting the height of the plant during biotic stress conditions.



Graph 2: Effect of Treatments on Plant Height of *Brassica juncea*

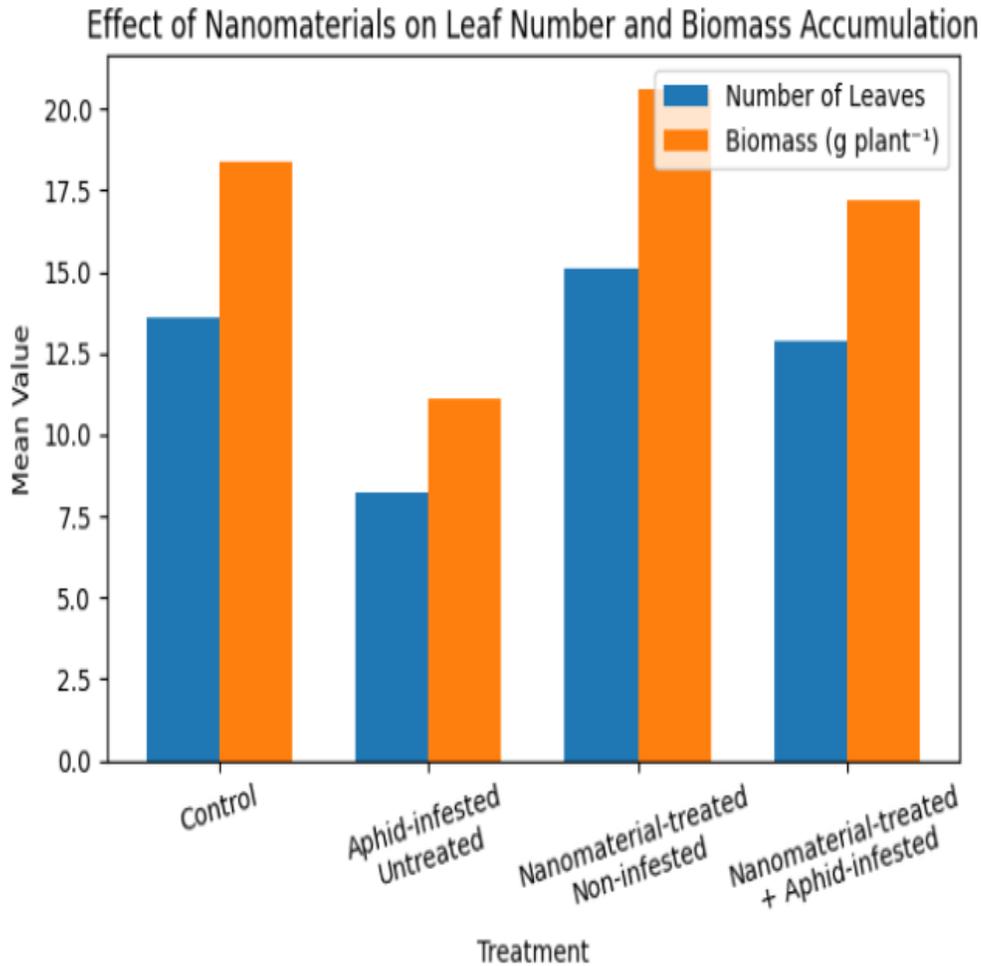
Graph 2 indicates that aphid infestation greatly inhibited plant height of mustard, which means that it reduced the growth of plants. Nanomaterial treatment increased the height of plants under both normal and aphid stress conditions where it significantly increased growth under aphid stress conditions, which showed that nanomaterials were able to overcome the inhibitory effect of insects on plant growth.

Table 3. Effect of Nanomaterials on Leaf Number and Biomass Accumulation

Treatment	No. of Leaves (plant ⁻¹)	Biomass (g plant ⁻¹)
Control	13.6 ± 1.1	18.4 ± 1.3
Aphid-infested, Untreated	8.2 ± 0.9	11.1 ± 1.0
Nanomaterial-treated, Non-infested	15.1 ± 1.2	20.6 ± 1.5
Nanomaterial-treated + Aphid-infested	12.9 ± 1.0	17.2 ± 1.2

Interpretation: In Table 3, the influence of the nanomaterial application on the production of leaves and biomass among the mustard plants has been brought out. The untreated plants infested with the aphids had significant decrease of the number of leaves and biomass and this showed that the insect stress significantly inhibited the growth. On the contrary, non-infested plants treated with

nanomaterials had the highest number of leaf and biomass (indicating better vegetative growth). It is worth noting that the application of nanomaterial in the aphid-infested condition had highly enhanced both parameters over the untreated infested plants. Such results indicate that nanomaterials facilitate the biomass growth and counter the negative impact of aphid-induced stress on *Brassica juncea* partially.



Graph 3: Effect of Nanomaterials on Leaf Number and Biomass Accumulation

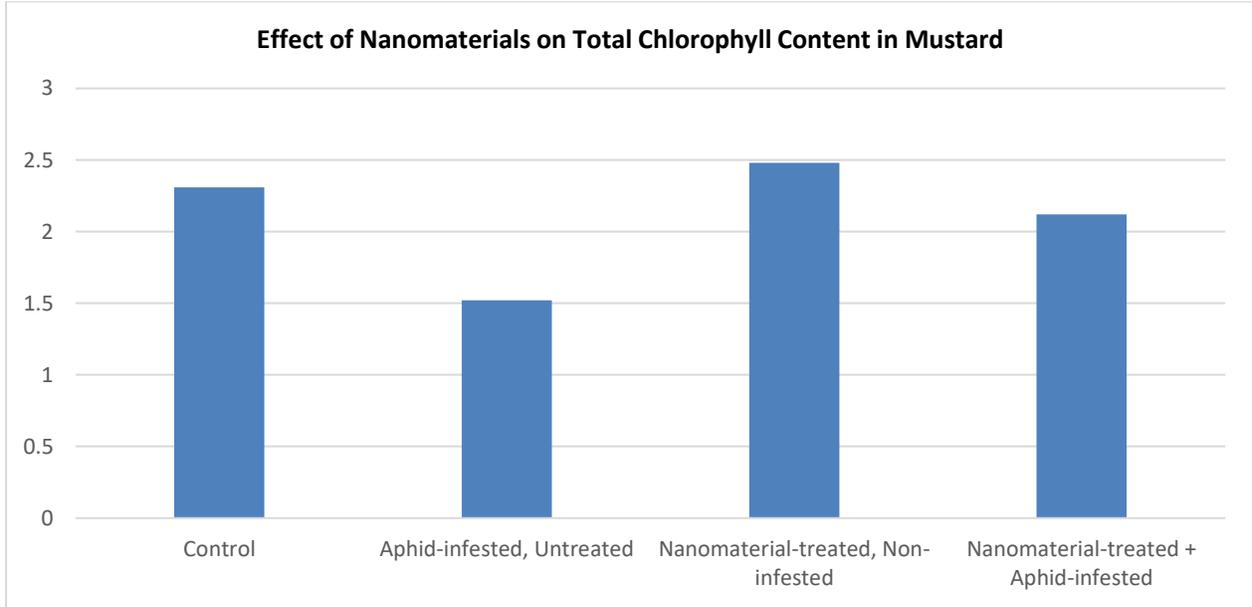
The graph 3 indicates that aphid infestation caused a great decrease in the number and biomass of the leaves of mustard plants. The Nanomaterial treatment increased the parameters in both normal condition and a significant increase in the number of leaves and increase in biomass in case of aphid stress, which shows that there was effective mitigation of the Aphid-induced growth suppressions.

Table 4. Chlorophyll Content in Mustard Leaves under Different Treatments

Treatment	Total Chlorophyll (mg g ⁻¹ FW)
Control	2.31 ± 0.12
Aphid-infested, Untreated	1.52 ± 0.10
Nanomaterial-treated, Non-infested	2.48 ± 0.14
Nanomaterial-treated + Aphid-infested	2.12 ± 0.11

Interpretation: Table 4 reveals that, in aphid-infested untreated mustard plants ($1.52 \pm 0.10 \text{ mg g}^{-1} \text{ FW}$), the total chlorophyll content reduced significantly, which results in the significant loss of photosynthetic apparatus under the stress of aphid feeding. Conversely, non-infested plants treated with nanomaterials had the highest chlorophyll content ($2.48 \pm 0.14 \text{ mg g}^{-1} \text{ FW}$) that indicates an increased

photosynthetic performance of the plant and stability of the pigments. Notably, the nanomaterial-treated plants with aphid infestation had a much higher amount of chlorophyll ($2.12 \pm 0.11 \text{ mg g}^{-1} \text{ FW}$) than the infested plants that were not treated with nanomaterials, which shows the protective nature of nanomaterials in aphid-infested mustard plants.



Graph 4: Effect of Nanomaterials on Total Chlorophyll Content in Mustard

In this graph 4, it is revealed that the aphid infestation causes a considerable loss in the total chlorophyll content of mustard, whereas the nanomaterial treatment is found to prevent the loss of chlorophyll contents under aphid induced stress.

Table 5. Biochemical Parameters of Mustard under Aphid Stress and Nanomaterial Treatment

Treatment	Protein (mg g ⁻¹ FW)	Carbohydrate (mg g ⁻¹ FW)	Antioxidant Activity (Units g ⁻¹)
Control	38.4 ± 2.0	52.6 ± 2.4	21.3 ± 1.5
Aphid-infested, Untreated	26.1 ± 1.8	37.8 ± 2.1	14.6 ± 1.2
Nanomaterial-treated, Non-infested	41.7 ± 2.2	55.9 ± 2.6	24.8 ± 1.6
Nanomaterial-treated + Aphid-infested	35.6 ± 2.0	49.1 ± 2.3	22.9 ± 1.4

Interpretation: Table 5 shows how aphid infestation and treatment with nanomaterials affects important biochemical parameters of mustard plants. The untreated plants infested with aphides experienced significant decrease in protein and carbohydrate levels and reduction in antioxidant activity, which showed that metabolism was disturbed, and that there was oxidative stress. Conversely, the highest concentrations of proteins, carbohydrates, and

antioxidant activity of plants treated by nanomaterials under the non-infested condition were observed, indicating the improvement of metabolic efficiency. Notably, nanomaterial use during aphid stress had a great effect on all the biochemical parameters relative to untreated infested plants. This is an indication that nanomaterials enhance antioxidant defense and aid in balancing metabolism within *Brassica juncea* subjected to aphid stress.

Table 6. Statistical Significance of Treatment Effects (ANOVA)

Parameter	F-value	p-value	Significance
Germination (%)	18.72	<0.05	Significant
Plant height	21.34	<0.05	Significant
Leaf number	16.89	<0.05	Significant
Biomass	19.45	<0.05	Significant
Chlorophyll content	22.61	<0.05	Significant
Biochemical parameters	24.18	<0.05	Significant

Interpretation: The findings of ANOVA to determine the statistical significance of treatments on different growth, physiological, and biochemical parameters of mustard are as summarized in Table 6. The F-values of all the parameters, germination, plant height, number of leaves, biomass, chlorophyll content, and biochemical properties were high with a p-value of less than 0.05 indicating that there were statistically significant differences in treatments. This proves that the presence of aphids' infestation and the use of nanomaterial were both prominent factors that affected the growth and metabolism of mustard. The findings support the credibility of the experimental data and confirm that the nanomaterial treatments were efficient in regulating the responses of the plants under the stress of aphid.

V. DISCUSSION

The present study clearly demonstrates that aphid infestation (*Lipaphis erysimi*) causes significant reductions in growth, physiological, and biochemical parameters of *Brassica juncea*. Decreased seed germination, plant height, leaf number, biomass, chlorophyll content, and metabolic constituents observed under aphid stress reflect severe disruption of photosynthesis, nutrient allocation, and cellular metabolism. Similar growth suppression in mustard due to sap-sucking insect stress has been widely reported in earlier studies (War et al., 2012) [5]. Enhanced seed germination and seedling vigour in the presence of nanomaterials in both normal and aphid stressed plants signal the positive effect of nanomaterials in stimulating metabolic processes and

nutrient supply. Similar improvement in germination and early development of mustard after the application of nanoparticles has been also observed by Mazumder et al. (2020) [26], who explained the same by enhanced enzyme activity and uptake of micronutrients.

The infesting by aphids significantly depressed the vegetative growth parameters, especially the height and biomass of the plant, because of repeated feeds on the phloem and the inhibition of photosynthetic efficiency. Nevertheless, aphid stress under mitigated insect-induced growth inhibition was greatly recovered by nanomaterial application, which suggests that these growth characteristics are notably restored under aphid stress. Francis et al. (2024) [23] have reported similar recovery of vegetative growth under biotic stress in the case of nanomaterials use, which confirms the growth-stimulating and stress-reducing effects of nanoparticles.

Reduction in the chlorophyll content of the aphid-infested untreated plants serves as evidence of the destruction of the photosynthetic system and augmented oxidative stress. Conversely, the plant treated with nanomaterials had greater chlorophyll values even when infested by aphids, implying the protection of the photosynthetic pigments. Similar results of chlorophyll retention in plants treated with nanoparticles were recorded in relation to chlorophyll maintenance in plants under stress (Djanaguiraman et al., 2024) [4], with the authors attributing such retention to the enhanced antioxidant defense systems.

Biochemical analysis also showed that aphid stress had a major impact on protein, carbohydrate, and antioxidant activity which indicated imbalance in metabolism and oxidative damage. The treated plants by nanomaterials had significant advances on these biochemical parameters in case of aphid stress, which may signify better metabolic efficiency and tolerance to oxidative stresses. Dimkpa and Bindraban (2017) [7] have also reported similar increases in biochemical performance after the application of nanoparticles.

In general, the statistically significant differences of treatments prove the validity of nanomaterials in reducing aphid-induced stress. The results indicate the possible potential of the nanomaterials as a sustainable and environmentally friendly solution to

enhance growth and stress resistance in mustard when exposed to insects.

VI. CONCLUSION

The current paper is of the opinion that the infestation with mustard aphid (*Lipaphis erysimi*) has a serious negative effect on the growth, physiological functioning, and biochemical stability of Brassica juncea as the germination, vegetative growth, chlorophyll level, and metabolic constituents were significantly reduced. Nanomaterials chosen were used successfully to reduce stress caused by aphids through enhancing germination of seeds, plant height recovery, the number of leaves, biomass accumulation, and preservation of photosynthetic pigments. Increased protein, carbohydrate, and antioxidant activities in plants treated with nanomaterials in aphid stress also exhibit increased metabolic effectiveness and tolerance to oxidative stress. These treatment effects are statistically significant, which evidences the credibility of these observations and demonstrates the importance of nanomaterials in regulating the plant defense and growth processes under biotic stress. The results overall indicate that the application of nanomaterials is a promising, environmentally friendly, and sustainable method of enhancing mustard growth and resistance to aphid infestation, which could be relevant to integrated pest and nutrient control in the production of oilseeds.

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