Application of Nanomaterials on Germination and Biochemical Parameters of Mustard (*Brassica juncea*) and Its Comparative Analysis under Insect-Induced Stress

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***Abstract*—The productivity of mustard (*Brassica juncea L.*), a significant oilseed crop in India, is heavily reliant on early seedling establishment and good seed germination. One of the most significant biotic restrictions on mustard production is insect-induced stress, which results in decreased germination, physiological imbalance, and compromised biochemical activities. To evaluate the effects of nanomaterials on mustard (*Brassica juncea*) seed germination and metabolic parameters under both normal and insect-induced stress conditions. The study was carried out in controlled laboratory and pot cultivation settings utilizing a fully randomized methodology. 60 uniform, healthy mustard seeds were chosen at random and split evenly between the control and nanomaterial-treated groups. Selected metal and metal oxide nanoparticles were used for seed priming. Mustard aphids (Lipaphis erysimi) were used to create insect-induced stress. The following metrics were noted: germination %, germination index, and seedling vigor index. Seed germination and seedling vigor were greatly enhanced by nanomaterial treatment both under normal and insect-induced stress conditions. The proportion of germination in plants treated with nanomaterials rose from 60% in stressed control plants to 80%. When compared to controls, treated seedlings showed higher vigor and germination indices. Increased protein concentration, soluble sugars, chlorophyll content, and antioxidant enzyme activity were found in nanomaterial-treated plants through biochemical analysis, suggesting better metabolic stability and stress tolerance. The current study comes to the conclusion that the use of nanomaterials significantly and favorably affects mustard (*Brassica juncea*) seed germination, seedling vigor, and biochemical parameters, especially when insect-induced stress is present.**

***Index Terms*—Mustard (*Brassica juncea*), Nanomaterials, Seed Germination, Insect stress, biochemical parameters, Antioxidant activity**

I. INTRODUCTION

Particularly in India, mustard (*Brassica juncea L.)* is a key oilseed crop that boosts the agricultural economy and production of edible oil [1]. The effectiveness of seed germination and the correct operation of biochemical processes in the early stages of development have a significant impact on its growth and yield [2]. Infestation by insects however, still remains one of the biggest biotic constraints on the production of mustard leading to a reduction in germination, impaired metabolic activities and loss of yields. Recently, there has been a significant interest in the agricultural sciences about the possible use of nanotechnology to increase plant growth, metabolism, and stress tolerance [3]. Nanomaterials (NMs) including iron oxide nanoparticles (FeO 3-NPs), “zinc oxide nanoparticles (ZnO-NPs), and silver nanoparticles (AgNPs)” are being increasingly examined as potential plant nutrient delivery and seed priming agents and as plant protectants [4].

Recent advances in agricultural nanotechnology have resulted in nanomaterials being considered as viable technologies to enhance crop performance and stress tolerance [5]. Due to their unique characteristics (i.e., their small size in nanoscale, high surface reactivity, high bioavailability), nanomaterials are able to interact with plant systems. Their applications in agriculture have shown potentials of improving antioxidant defense mechanism, absorption of nutrients, enzyme activation and seed germination [6]. Mustard (*Brassica juncea L.)* is an essential element of sustainable agriculture, and it is widely cultivated because of the presence of oil in its seeds. The early seedling growth and seed germination are important attributes in the success of mustard production as it influences the vigor of the crop and the final yield [7]. These are particularly vulnerable stages of early development, and insects may induce stress which in turn results in oxidative damage, physiological imbalance and altered biochemical pathways [8].

Limited studies have investigated the interactive effects of the use of nanomaterials and insect-imposed stress on mustard plants even though interest on nanotechnology-based agricultural interventions is on the rise [9]. A comparison between the treated and untreated plant subjected to pest stress condition is necessary to determine the practical utility of nanomaterials in crop protection and enhancement of crop productivity [10]. Therefore, the aim of the first research is to analyze the effectiveness of nanomaterials with insect induced stress and to determine the effect of nanomaterials on *Brassica juncea* germination and biochemical indices [11].

1.1. INSECTS INDUCED STRESS IN MUSTARD

In its life-cycle, mustard *(Brassica juncea L.*) is especially susceptible to a wide range of insect pests that induce extreme biotic stress, particularly during germination and early seedling development [12]. Some of the major insect pests that result in major physiological and biochemical disturbances include flea beetles, caterpillars, painted bugs (Bagrada hilaris), mustard aphids (Lipaphis erysimi), and others that feed on seedlings, leaves, stems, and reproductive tissues [13]. The insect feeding directly causes mechanical damage to the plant tissues with a reduction in the photosynthetic surface area and loss in the cellular integrity. The regular metabolic processes are also interfered with by the continual sucking of sap and injection of poisonous saliva by insects [14]. These interactions culminate in insect-induced stress which is characterized by a reduced germination rate, poor seedlings, retarded growth and development [15].

1.2. NANOMATERIALS AND INSECTS STRESS MITIGATION

The insect infestation is a serious biotic stress affecting plant development, physiology, as well as yield negatively and disrupting metabolic and biochemical processes [16]. Recent advances in agricultural nanotechnology have introduced the possibility of nanoparticles as helpful tools to alleviate crop stress caused by insects. The interaction of nanomaterials with plant tissues and insect pests can occur effectively due to its ability to interact with the surface area, nanoscale size and enhanced reactivity [17]. Nanomaterials can decrease the stress of pests by improving the physiological resilience of plants and increasing their defense mechanisms. When are attacked by insects, maintain chlorophyll levels, enhancing the functions of antioxidant enzymes, and regulate protein and carbohydrate metabolism. Moreover, some nanomaterials possess insecticidal or insect-repellent properties, which reduce the damage and infestation of pests [18].

Nanomaterials also offer a viable and ecologically friendly alternative to the conventional chemical pesticides through raising the resilience of plants and reducing physiological damage by insects [19]. There is a great potential to increase crop yields, promote environmentally friendly ways of farming, and support integrated pest management efforts when are applied judiciously [20].

AIM:

To evaluate the effects of nanomaterials on mustard (*Brassica juncea*) seed germination and metabolic parameters under both normal and insect-induced stress conditions.

OBJECTIVE:

I. To evaluate the effects of nanomaterials on seed germination and biochemical parameters of mustard (*Brassica juncea)*.

II. To evaluate mustard plants germination capability and metabolic reactions after applying nanomaterials under both normal and insect-induced stress condition.

II. REVIEW OF LITERATURE

MERKLE ET AL., (2025) reported that allelopathy and competition, a variety of plant species from the "Poaceae, Cannabaceae, and Brassicaceae families are employed as cover crops to reduce weeds and volunteer crops. In order to improve the plant species Avena strigosa, Cannabis sativa, and Sinapis alba's" capacity to suppress weeds, this study investigated the effects of artificially induced stress on their physiological processes, total phenolic content (TPC), and allelopathic potential at an early growth stage. A few days after treatment, there was little to no change in the maximum quantum yield of photosystem II and shoot dry matter in all three plant species (DAT) [21].

VARADHARAJAN ET AL., (2025) highlighted that Abiotic and biotic environmental challenges are among the many that plants must deal with. These pressures shorten the lifespan of plants and lower the output of agricultural crops. The molecular, cellular, and developmental processes of plant systems can all be hampered by these stresses. Multi-omics computational methods provide an important tool for assessing the plant's biomolecular pool, which is essential for preserving homeostasis and signaling response to environmental changes. The research of plant resistance mechanisms is made easier by integrating many omics data layers, including "proteomics, metabolomics, ionomics, interactomics, and phenomics" [22].

XIA ET AL., (2023) reported that glucosinolates (GSLs) are unique and crucial insect defense chemicals produced by cruciferous vegetables. Meanwhile, it remains unclear how insect feeding causes glucosinolates in Brassica to mediate insect resistance and how plants regulate the strength of their anti-insect defense response. According to the functional enrichment data, elevated DEGs were shown to significantly enrich the pathways associated with the manufacture of glucosinolate and jasmonic acid. This implies that mustard may provide herbivory protection by promoting JA production, which in turn promotes the buildup of GSL [23].

TIEMANN (2021) reported that exudates from bacteria, fungi, and roots have an impact on the community dynamics of soil micro-environments because have the ability to favor certain functional classes of microorganisms. Members of this community include "arbuscular mycorrhizal fungus (AM) and plant growth promoting rhizobacteria (PGPR)", which have symbiotic connections with plants and are crucial in initiating induced systemic resistance (ISR), which leads to defensive "priming." As a result, "primed" plants are able to launch quicker and more potent defense mechanisms against disease and insect attacks in the future. Four genotypes of barrel medic plants "(Medicago truncatula), pea aphids (Acyrthosiphon pisum)", and microbial communities found in three field collected soils and one commercial topsoil comprised the biological system in this study [24].

SHARMA AND MATHUR (2020) Microbial fertilizers are becoming more and more well-liked as an environmentally friendly nutritional supplement for plant growth. It is yet unknown, though, how these bacteria affect plant-induced reactions and how late-arriving herbivores are affected. One of the first reactions that plants experience after insect herbivory is oxidative stress. Thus examined the impact of "vesicular-arbuscular mycorrhiza (VAM), phosphorus solubilizing bacteria (PSB)", and their combination on oxidative stress in Brassica juncea against herbivorous Spodoptera litura. The results showed that plants fed with PSB sometimes had higher levels of APX and GR. On the other hand, after 72 hours, plants fed with VAM demonstrated an active systemic response to herbivory, as evidenced by an increase in all six enzymes [25].

FARAZ ET AL., (2023) reported that nanoparticles (NPs) are now being used in agricultural fields to the point where people are thinking about using them instead of commercial fertilizers. This study examined the use of "copper oxide nanoparticles (CuO NPs") as seed primers. At the maximum vegetative growth stage, or 45 days after sowing, the growth indices of Brassica juncea, including "phenotypic parameters, photosynthetic characteristics, and biochemical parameters", were assessed. The seeds were sown in pots and left to grow organically after those priming times. The optimal concentration of CuO NPs was found to be 4 mg/L for 30 minutes of seed priming. This resulted in significant increases in "shoot length (30%), root length (27%), net photosynthetic rate (30%), internal CO2 concentration (28%), and proline content (41%)" [26].

III. METHODOLOGY

The study was carried out utilizing a fully randomized design in a controlled laboratory and pot cultivation setting. Each treatment was maintained in triplicate, and mustard seeds were split into control and nanomaterial-treated groups. Both normal and insect-induced stress conditions were used for the comparative analysis. A reputable agricultural research facility provided certified mustard (*Brassica juncea)* seeds. For the experiment, uniform, healthy seeds free of obvious damage were chosen. A total 60 healthy mustard seeds (*Brassica juncea)* were chosen for the current investigation based on their consistent size and appearance. Equal numbers of seeds were assigned to the nanomaterial-treated group and the control group at random. The chosen sample size was thought to be sufficient for assessing how nanomaterials affected mustard germination and metabolic measures under both normal and insect-induced stress conditions.

➢ Sampling technique
- Sample random sampling technique adopted
- Seeds randomly selected from a bulk seeds lot
- Equal probability given to all seeds for selection
- Random assignment of seeds to control and treatment groups

➢ Sample selection criteria

✓ INCLUSION
- Seeds of brassica juncea with uniform size and color
- Seeds free from visible physical damage
- Seeds showing no sign of fungal or insects infestation
- Seeds with moisture content within recommended limits

✓ EXCLUSION
- Broken or shriveled seeds
- Seeds with visible disease symptoms
- Seeds with abnormal size or shape
- Seeds damaged during handling or storage

1.3. Nanomaterials selection and preparation: The metal oxide nanoparticles (zinc oxide, ZnO), metal (silver, Ag), or iron oxide (Fe_2O_3) nanoparticles were the most common and selected nanomaterials to be studied. Through the preparation of nanoparticle suspensions, to ensure stability, were prepared with distilled water at predetermined concentrations and blended evenly by ultrasonic stirring.

1.4. Seed treatment with nanomaterials: Mustard seeds were thoroughly cleaned with distilled water after being surface sterilized with a 1% sodium hypochlorite solution. After that, the seeds were immersed in suspensions of nanomaterials for a predetermined amount of time, whereas the control seeds were just immersed in distilled water. Before being sown, the seeds were allowed to air dry at room temperature following treatment.

1.5. Germination experiment: Petri dishes covered with moist filter paper were used to hold the treated and control seeds, which were then incubated at the ideal temperature and light. Seedling vigor, germination index, and germination percentage were measured on a regular basis.

1.6. Induction of insects –induced stress
- Mustard aphids (Lipaphis erysimi) used for stress induction
- Controlled aphid population introduced at seeding stage
- Uniform insects pressure maintained

1.7. Biochemical analysis
- Leaf sample collected at defined growth stage
- Chlorophyll content estimation
- Total soluble protein estimation
- Soluble sugar estimation
- Antioxidant enzyme activity analysis

1.8. Comparative evaluation
- Comparison between treatment and untreated plants
- Assessment under normal and insect –stress condition

IV. RESULT

4.1 EFFECTS OF NANOMATERIAL APPLICATION ON GERMINATION OF MUSTARD (*BRASSICA JUNCEA*)

TABLE 1: GERMINATION PERFORMANCE OF MUSTARD SEEDS (N=60)

Experimental condition	Group	Seeds used	Seeds germination
Normal condition	Control	30	80.0
	Nanomaterial treated	30	90.0
Insects-induced stress	Control	30	60.0
	Nanomaterial treated	30	80.0

Interpretation: According to the findings, mustard seed germination was enhanced by nanomaterial treatment in both normal and insect-induced stress scenarios. Insect stress significantly reduced germination in untreated seedlings, but germination was higher in seeds treated with nanomaterials than in the control group. This suggests that nanomaterials can improve germination and lessen the negative consequences of stress caused by insects.

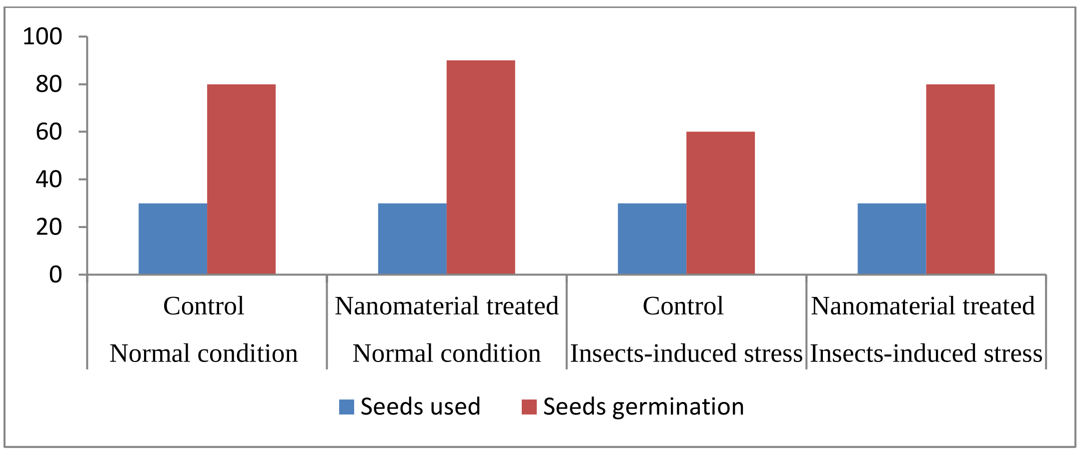

Fig 4.1: effects of nanomaterials on germination and biochemical parameters of Mustard under insect-induced stress

4.2 GERMINATION INDEX AND SEEDLING VIGOR

TABLE2: GERMINATION INDEX AND SEEDLING VIGOR

Treatment	Condition	Germination index	Seedling vigor index
Control	Normal	62 ± 0.3	980 ± 32
Nanomaterials treatment	Normal	8.1 ± 0.4	1320 ± 41
Control	Insect stress	4.5 ± 0.2	710 ± 28
Nanomaterial treated	Insect stress	6.9 ± 0.3	1150 ± 37

INTERPRETATION Reveals that in the conditions of normal and insect stress, the nanomaterial treatment significantly enhanced the germination index and seedling vigor index. In the normal conditions, the germination index and seedling vigor of nanomaterials treated seeds were greater as compared to the control. The measures were greatly reduced in control plants by insect stress, but in seedlings treated with nanomaterials the measures were much higher which shows that nanomaterials are important to seedling performance and stress tolerance.

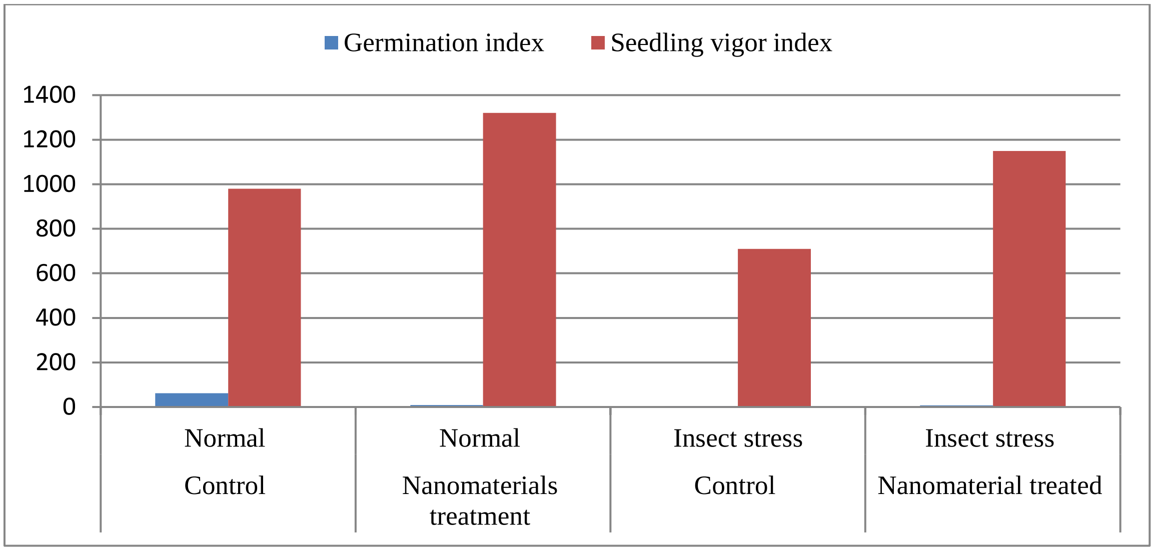

FIG 4.2: IMPACT OF NANOMATERIAL TREATMENT ON SEEDLING VIGOR AND GERMINATION INDEX IN BOTH NORMAL AND INSECT STRESS SITUATIONS

4.3. EFFECTS OF NANOMATERIAL ON BIOCHEMICAL PARAMETERS

TABLE 3: BIOCHEMICAL PARAMETERS UNDER NORMAL CONDITION

Parameter	Control	Nanomaterial treated
Chlorophyll ($mg^{-1}gFW$)	1.58 ± 0.05	2.26 ± 0.07
Total soluble protein (mg^{-1} g FW)	18.1 ±0.6	25.4 ± 0.8
Soluble sugars ($mg^{-1}gFW$)	12 .5 ± 0.4	18.2 ±0.6

INTERPRETATION: The results indicate that compared to the control, the nanomaterial treatment had a significant positive effect on the biochemical parameters of mustard plants. More chlorophyll, total soluble protein and soluble sugar were observed in treated plants indicating improved photosynthetic capacity, metabolic activity and overall physiological performance due to the effects of nanomaterial use.

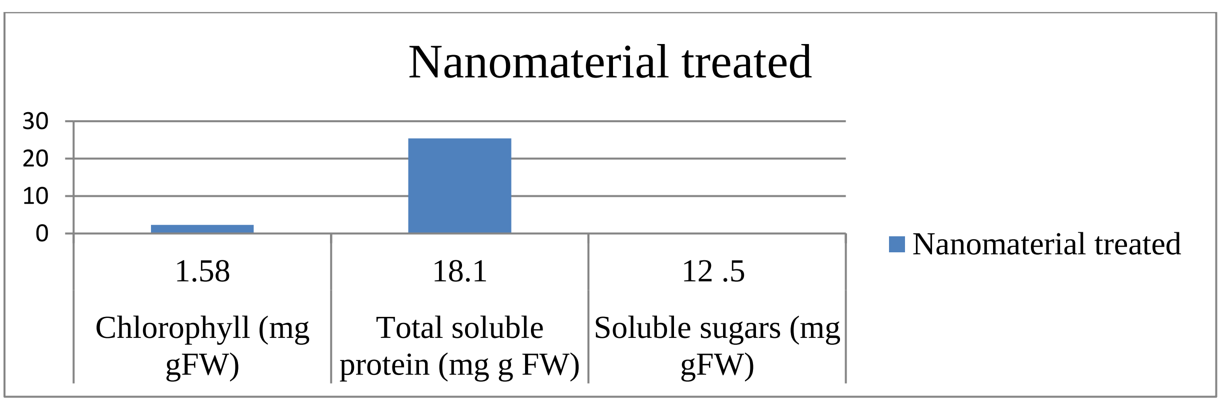

FIG 4.3: EFFECTS OF NANOMATERIALS AND INSECTS ON SEED GERMINATION INDEX

4.4. BIOCHEMICAL RESPONSE UNDER INSECT-INDUCED STRESS

TABLE 4: BIOCHEMICAL PARAMETERS UNDER INSECTS STRESS

Parameter	Control+ Stress	Nano treated + stress
Chlorophyll (mg-^{1}g FW	1.09 ± 0.04	1.92 ± 0.06
Total soluble protein	13.6 ± 0.5	21.1 ± 0.7
Soluble sugars	9.3 ± 0.3	15.7 ± 0.5
Antioxidant enzymes activity	41.8 ±1.2	69.4 ± 2.0

INTERPRETATION Stress by insects has led to marked reduction of protein, soluble sugars and chlorophyll content in control plants, thus indicating impairment of metabolism by stress. Conversely, plants that received nanomaterials exhibited enhanced antioxidant enzyme activity and maintained significantly high biochemical levels, which showed that the use of nanomaterials was effective in enhancing stress tolerance and preserving metabolic functions in the process of insect stress.

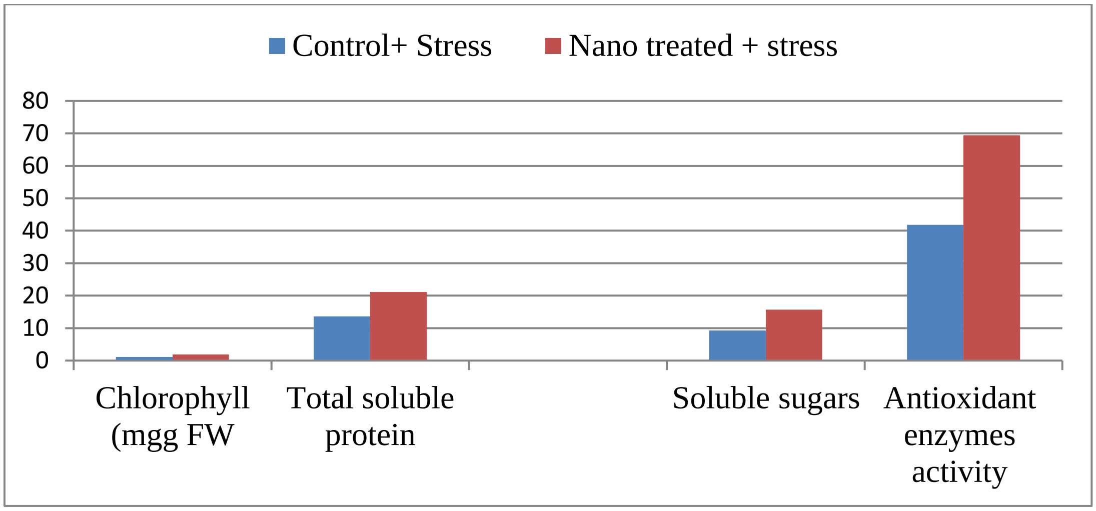

FIG 4.4: "IMPACT OF NANOMATERIAL TREATMENT ON BIOCHEMICAL AND ANTIOXIDANT RESPONSES UNDER STRESS"

4.5. COMPARATIVE EVALUATION OF TREATMENT

TABLE 4: COMPARATIVE EFFECTS OF NANOMATERIALS

Parameter	Control (stress)	Non treated (stress)	% improvement
Germination	60.0	80.0	33.3
Chlorophyll content	1.09	1.92	76.1
Protein consent	13.6	21.1	55.1
Antioxidant activity	41.8	69.4	66.0

INTERPRETATION The comparative information indicates that the treatment with nanomaterials led to significant improvement of all the parameters measured in case of stress conditions due to insects. Germination was elevated by 33.3 per cent and antioxidant activity, protein level and chlorophyll content were elevated by 76.1, 55.1 and 66.0 per cent, respectively, versus the stressed control. The findings would be able to prove the hypothesis that nanomaterials can promote the physiological and biochemical resistance of mustard plants to insect stress.

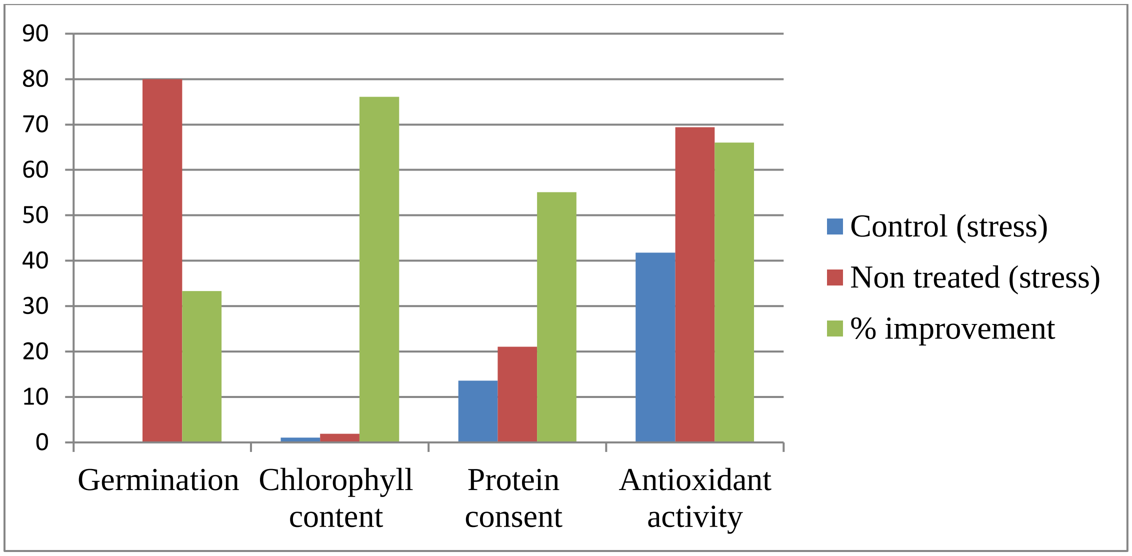

FIG 4.5: "EFFECT OF TREATMENT ON GERMINATION, CHLOROPHYLL CONTENT, PROTEIN CONTENT, AND ANTIOXIDANT ACTIVITY UNDER STRESS CONDITIONS"

V. DISCUSSION

The study's findings unequivocally show that seed germination is positively impacted by nanomaterial treatment in both normal and insect-induced stress situations. Seeds treated with nanomaterials showed a greater germination rate (90%) under normal conditions than the control group (80%), suggesting a growth-promoting impact even in the absence of stress. Insect-induced stress dramatically decreased germination in untreated control seeds (60%), whereas under the same stress conditions, nanomaterial-treated seeds demonstrated a notable improvement in germination (80%). These results imply that nanomaterials both improve baseline germination performance and lessen the negative impacts of stress caused by insects. Ushahra et al., (2014) who have been found that biogenic nanoparticles made from Tridax procumbens on several biochemical parameters, seed germination, and seedling growth in four Eruca sativa cultivars with low germination rates. Biogenic nanoparticles were applied to seeds at two different concentrations (30 and 40 ppm); 30 ppm was found to be the most effective and was chosen for further research. First, the impact of biogenic nanoparticles on vigor index, fresh and dry matter, shoot and root length, germination rate, speed of germination, coefficient of germination, and mean germination time was investigated [27].

When compared to the control, the nanomaterial treatment greatly increased the germination index and seedling vigor in both normal and insect-stress conditions. Insect stress decreased the vigor and germination performance of untreated seeds, but the application of nanomaterials successfully countered this reduction, improving seedling establishment and stress tolerance. Hatami (2017) who have been found that applying nanomaterials to plants for agricultural purposes has gained popularity recently because of their special qualities. According to published research, engineered nanoparticles have an impact on cell structure, function, plant growth, and seed germination. The impacts of manmade nanomaterials on plants, particularly food and/or industrial crops, remain, nevertheless, poorly understood. The effects of diverse nanosized materials (metal or metal oxide nanoparticles and carbon-based nanomaterials) on plant physiology are complicated; even the same kind of these materials may have distinct biological effects on different plant species [28].

The findings show that after treatment, plants performed significantly better under stress. Chlorophyll content, protein content, and antioxidant activity all significantly increased by 76.1%, 55.1%, and 66.0%, respectively, while germination increased by 33.3%. These results show that the treatment successfully reduces damage caused by stress by increasing physiological and biochemical characteristics, which in turn increases total stress tolerance. Surender et al., (2013) In order to assess the relative water content, soluble protein content, total chlorophyll content, and yield variations caused by water deficiency, twelve cultivars of banana plants were grown in field circumstances under two irrigation regimes during ratoon season. When the soil water potential reached 80% ASM for the wet treatments and 50% ASM for the stressed treatment plots, irrigation was provided. The soil moisture release curve was used to determine the ASM. Using a pressure plate membrane device, the soil moisture content was determined [29].

VI. CONCLUSION

The current study comes to the conclusion that the use of nanomaterials significantly and favorably affects mustard (*Brassica juncea)* seed germination, seedling vigor, and biochemical parameters, especially when insect-induced stress is present. In untreated plants, insect stress significantly decreased germination performance and interfered with important metabolic processes, as seen by decreased levels of soluble sugars, protein, chlorophyll, and antioxidant enzyme activity. On the other hand, plants treated with nanomaterials showed greater early establishment and growth, as seen by increased seedling vigor, a higher germination index, and an improved germination percentage. The biochemical results also showed that, even in the face of insect pressure, nanomaterials contributed to the maintenance of increased chlorophyll content and metabolic efficiency. Increased activity of antioxidant enzymes in treated plants indicates a better defense against oxidative damage brought on by insect invasion. Comparative investigation revealed that plants treated with nanomaterials had much better germination and physiological characteristics than stressed controls.

REFERENCE

[1] Bhattacharya S, Sinha S, Dey P, Das N, Maiti MK. Production of nutritionally desirable fatty acids in seed oil of Indian mustard (Brassica juncea L.) by metabolic engineering. Phytochemistry reviews. 2012 Jun;11(2):197-209.

[2] Mondal S, Bose B. Impact of micronutrient seed priming on germination, growth, development, nutritional status and yield aspects of plants. Journal of Plant Nutrition. 2019 Nov 26;42(19):2577-99.

[3] Zhao L, Lu L, Wang A, Zhang H, Huang M, Wu H, Xing B, Wang Z, Ji R. Nano-biotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance. Journal of agricultural and food chemistry. 2020 Jan 31;68(7):1935-47.

[4] Maity D, Gupta U, Saha S. Biosynthesized metal oxide nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management. Nanoscale. 2022;14(38):13950-89.

[5] El-Saadony MT, Saad AM, Soliman SM, Salem HM, Desoky ES, Babalghith AO, El-Tahan AM, Ibrahim OM, Ebrahim AA, Abd El-Mageed TA, Elrys AS. Role of nanoparticles in enhancing crop tolerance to abiotic stress: A comprehensive review. Frontiers in plant science. 2022 Nov 2; 13:946717.

[6] Fujita M, Hasanuzzaman M. Approaches to enhancing antioxidant defense in plants. Antioxidants. 2022 May 8;11(5):925.

[7] Shekhawat K, Rathore SS, Premi OP, Kandpal BK, Chauhan JS. Advances in agronomic management of Indian mustard (Brassica juncea (L.) Czernj. Cosson): an overview. International journal of Agronomy. 2012;2012(1):408284.

[8] Kodrík D, Bednářová A, Zemanová M, Krishnan N. Hormonal regulation of response to oxidative stress in insects—an update. International journal of molecular sciences. 2015 Oct 27;16(10):25788-816.

[9] Khattak WA, Ullah MW, Manan S, Islam SU, Khattak WA, Ul-Islam M. Emerging Applications and Future Trends of Agri-Nanotechnology. Revolutionizing Agriculture: A Comprehensive Exploration of Agri-Nanotechnology. 2024 Dec 25:429-58.

[10] Fu L, Wang Z, Dhankher OP, Xing B. Nanotechnology as a new sustainable approach for controlling crop diseases and increasing agricultural production. Journal of Experimental Botany. 2020 Jan 7;71(2):507-19.

[11] Mazumder JA, Khan E, Perwez M, Gupta M, Kumar S, Raza K, Sardar M. Exposure of biosynthesized nanoscale ZnO to Brassica juncea crop plant: morphological, biochemical and molecular aspects. Scientific Reports. 2020 May 22;10(1):8531.

[12] Yadav S, Rathee M. Sucking pests of rapeseed-mustard. InSucking pests of crops 2020 Oct 13 (pp. 187-232). Singapore: Springer Singapore.

[13] Aarwe R, Vishwakarma D, Rajput DS, Patidar S, Singh S, Raipuria N. Major Insect Pests of Mustard and Their Management. Major Pests and Diseases of Spices Crops and their Management. Empyreal publishing, India. 2023:68-79.

[14] Goggin FL, Quisenberry SS, Ni XinZhi NX. Feeding injury. InAphids as crop pests 2017 (pp. 303-322). Wallingford UK: CABI.

[15] Singh S. Investigation on the role of plant defensin proteins in regulating plant-Verticillium longisporum interactions in Arabidopsis thaliana (Doctoral dissertation).

[16] Dixit S, Sivalingam PN, Baskaran RM, Senthil-Kumar M, Ghosh PK. Plant responses to concurrent abiotic and biotic stress: unravelling physiological and morphological mechanisms. Plant Physiology Reports. 2024 Mar;29(1):6-17.

[17] Khandelwal N, Barbole RS, Banerjee SS, Chate GP, Biradar AV, Khandare JJ, Giri AP. Budding trends in integrated pest management using advanced micro-and nano-materials: Challenges and perspectives. Journal of environmental management. 2016 Dec 15;184:157-69.

[18] Pouthika K, Madhumitha G. A review on plant-derived nanomaterials: an effective and innovative insect-resistant strategy for alternate pesticide development. International Journal of Environmental Science and Technology. 2024 Jan;21(2):2239-62.

[19] Campos EV, do Espirito Santo Pereira A, de Oliveira JL, Villarreal GP, Fraceto LF. Nature-based nanocarrier system: an eco-friendly alternative for improving crop resilience to climate changes. Anthropocene Science. 2022 Sep;1(3):396-403.

[20] Barzman M, Bàrberi P, Birch AN, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, Hommel B, Jensen JE, Kiss J, Kudsk P, Lamichhane JR. Eight principles of integrated pest management. Agronomy for sustainable development. 2015 Oct;35(4):1199-215.

[21] Merkle M, Petschenka G, Belz R, Gerhards R. Enhancing Weed Suppression in Plants by Artificial Stress Induction. Journal of Crop Health. 2025 Feb;77(1):21.

[22] Varadharajan V, Rajendran R, Muthuramalingam P, Runthala A, Madhesh V, Swaminathan G, Murugan P, Srinivasan H, Park Y, Shin H, Ramesh M. Multi-Omics Approaches Against Abiotic and Biotic Stress—A Review. Plants. 2025 Mar 10;14(6):865.

[23] Xia R, Xu L, Hao J, Zhang L, Wang S, Zhu Z, Yu Y. Transcriptome Dynamics of Brassica juncea Leaves in Response to Omnivorous Beet Armyworm (Spodoptera exigua, Hübner). International Journal of Molecular Sciences. 2023 Nov 24;24(23):16690.

[24] Tiemann Z. Indirect Impact of Soil Microbial Communities on Plant-Aphid Interactions.

[25] Sharma G, Mathur V. Modulation of insect-induced oxidative stress responses by microbial fertilizers in Brassica juncea. FEMS Microbiology Ecology. 2020 Apr;96(4):fiaa040.

[26] Faraz A, Faizan M, D. Rajput V, Minkina T, Hayat S, Faisal M, Alatar AA, Abdel-Salam EM. CuO nanoparticle-mediated seed priming improves physio-biochemical and enzymatic activities of Brassica juncea. Plants. 2023 Feb 10;12(4):803.

[27] Ushahra J, Bhati-Kushwaha H, Malik CP. Biogenic nanoparticle-mediated augmentation of seed germination, growth, and antioxidant level of Eruca sativa Mill. varieties. Applied biochemistry and biotechnology. 2014 Sep;174(2):729-38.

[28] Hatami M. Stimulatory and inhibitory effects of nanoparticulate on seed germination and seedling vigor indices. Nanoscience and plant–soil systems. 2017 Feb 15:357-85.

[29] Surendar KK, Devi DD, Ravi I, Jeyakumar P, Velayudham K. Water stress affects plant relative water content, soluble protein, total chlorophyll content and yield of ratoon banana. International Journal of Horticulture. 2013 Apr 28;3.