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Effectiveness of Nanopriming Using *Padina minor* Nanoparticles on the Germination and Early Growth of Kopay Chili Pepper Seeds (*Capsicum annuum* L.)

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Abstract: This study aimed to evaluate the effects of nanopriming using *Padina minor* nanoparticles on the germination parameters and early seedling growth of Kopay chili pepper (*Capsicum annuum* L.) seeds, as well as to assess the physiological responses and enzyme activities associated with nanopriming treatment. The experiment was arranged in a completely randomized design (CRD) with five treatments: no priming, hydropriming, and nanopriming at concentrations of 100, 150, and 200 ppm, each with five replications. The observed parameters included time to germination emergence, germination potential, vigor index, root length, shoot length, and the activities of amylase and catalase enzymes. Data were analyzed using analysis of variance (ANOVA) at the 5% significance level, followed by Duncan's Multiple Range Test (DMRT). The results showed that nanopriming significantly accelerated germination emergence and increased root length, with the best response observed at 100 ppm. However, the treatment did not have a significant effect on germination potential, vigor index, shoot length, or the activities of amylase and catalase during the early germination phase. Thus, *Padina minor* nanopriming contributes to the improvement of specific early growth parameters, particularly those related to germination speed and root development.

Keywords: *Capsicum annuum* L.; nanopriming; *Padina minor*; germination; early growth

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INTRODUCTION

Chili pepper (*Capsicum annuum* L.) is a horticultural commodity of high economic value that is widely cultivated across many regions. In Indonesia, chili consumption in 2020 reached 549.48 thousand tons (Seth & Sebastian, 2024). Nationally, chili production showed an increasing trend, rising from 1.21 million tons in 2019 to 1.26 million tons in 2020 and 1.36 million tons in 2021. In contrast, a different pattern was observed in West Sumatra, where chili production declined over the same period, from 139,994 tons in 2019 to 133,190 tons in 2020 and 115,766 tons in 2021 (Ediwarman et al., 2023). This decline may be attributed to various factors, including environmental conditions, cultivation practices, and the quality of planting materials used. One of the fundamental determinants of successful chili cultivation is seed quality, particularly the ability of seeds to germinate rapidly and uniformly and to produce vigorous seedlings. Good seed vigor is essential because it determines the plant's initial capacity to adapt to suboptimal environmental conditions, including limited water availability during the early growth stage.

West Sumatra is one of Indonesia's major chili-producing regions and also has a high level of chili consumption (Hamidah et al., 2020). One prominent local variety in this region is Kopay chili, which originated in Payakumbuh City and was developed through selection and purification by local farmers. This variety has been favored for its high productivity and relative tolerance to several pests and diseases, giving it strong potential as a superior local variety of strategic value for farmers (Azani et al., 2024). Despite these advantages, Kopay chili remains sensitive to environmental conditions. Unfavorable environmental factors can inhibit important physiological processes such as photosynthesis and flower formation, thereby reducing productivity and harvest quality (Hussain et al., 2022). Stress conditions may also increase plant susceptibility to pest and disease attacks (Lippmann et al., 2019). Therefore, the Kopay variety represents an important model for investigating strategies to improve resilience and optimize growth in local chili cultivars, including seed priming technology.

Previous studies have shown that priming not only improves the speed and uniformity of germination, but also enhances early growth and seed viability. Priming can stimulate enzyme activity, increase cellular metabolism, and strengthen root and shoot development, thereby enabling plants to establish more effectively from the earliest growth stages (Farooq et al., 2017; Zhou et al., 2020). These mechanisms make priming an effective strategy for improving seed quality and plant performance, particularly in superior local varieties such as Kopay chili, which may require pre-sowing treatment to achieve their full potential.

One promising priming method is nanopriming, which involves the use of nanoparticle-containing solutions to stimulate seed growth and viability (Nile et al., 2022; Alamsjah et al., 2023). In addition to nanopriming, other priming methods include halopriming (salt solutions), hydropriming (water), osmopriming (osmotic agents), hormonal priming (plant hormone solutions), biopriming (microbial solutions), magnetopriming (under a magnetic field), and matripriming (solutions containing solid matrices) (Gammoudi et al., 2021; Suwirmen et al., 2022). Through these diverse mechanisms, priming offers an effective approach to improving the viability, growth, and performance of Kopay chili seeds from the earliest developmental stages.

In line with these developments, nanotechnology has opened new opportunities in agriculture, particularly in the development of more effective and efficient priming agents. Nanopriming is a novel technology that uses nanomaterials, especially nanoparticles, for seed priming. The nanoparticles used in nanopriming may be derived from metals, carbon-based materials, or plant extracts (Rhaman et al., 2022). As a recent innovation in seed priming, nanopriming offers advantages through the use of nanoparticles that can interact more efficiently with plant cells (Ozbay & Susluoglu, 2016). Nanoparticles possess unique characteristics, including a high surface-area-to-volume ratio, good thermal stability, and a greater capacity to interact with plant cells than conventional materials (Ye et al., 2021).

One biological resource with strong potential as a nanopriming agent is the seaweed *Padina minor*. Compared with other biological sources, *P. minor* is particularly promising because of its comprehensive content of bioactive compounds, including polysaccharides, phytohormones (such as auxins and cytokinins), antioxidants, amino acids, and essential minerals (Abdullah et al., 2021; Rouhi et al., 2021). This combination of compounds enables *P. minor* to function not only as a supplementary nutrient source but also as a biostimulant that strengthens plant defense mechanisms. Theoretically, antioxidants from *P. minor* may mitigate oxidative stress caused by drought, phytohormones may stimulate root and shoot growth to improve water uptake efficiency, while minerals and polysaccharides may support cellular metabolism and water retention in seed tissues (Pawar et al., 2018). Therefore, the application of *P. minor* nanoparticle extract to chili seeds has the potential to improve seed survival and promote optimal growth under drought stress conditions.

The effectiveness of priming is strongly influenced by the concentration of nanoparticles used. Najla (2025) reported that chili seed germination at a low concentration of *P. minor* extract (50 mg/L) was lower than that of the control and higher concentrations, indicating that this low dose was insufficient to produce an optimal effect. Bhuvaneshwari et al. (2020) showed that ZnO nanoparticles synthesized using *Halimeda opuntia* extract at a concentration of 50 ppm significantly increased germination percentage and seedling growth in maize. Similarly, Wlodarczyk and Smolinska (2022) reported that different concentrations of ZnO nanoparticles (50, 150, and 250 mg/L) affected all germination parameters in tomato seeds.

Although previous studies have demonstrated the positive effects of nanoparticles on chili seed germination, the available evidence remains limited. Najla (2025) tested *P. minor* extract on the Kopay chili variety, but the evaluation was confined to germination percentage and early growth. Physiological parameters and enzymatic activities associated with drought stress tolerance were not examined, and the range of concentrations tested remained limited. Therefore, the effectiveness of *P. minor* nanopriming in Kopay chili seeds, particularly in enhancing drought tolerance and modulating physiological and enzymatic responses across different concentrations, still requires further investigation.

Based on the background described above, this study aimed to evaluate the effect of nanopriming using *Padina minor* nanoparticles on the germination parameters and early growth of Kopay chili (*Capsicum annuum* L.) seeds, as well as to assess the physiological responses and enzymatic activities induced by nanopriming treatment. The findings of this study are expected to provide scientific evidence regarding the effectiveness of *Padina minor* nanopriming in improving the viability and growth of Kopay chili seeds and to serve as a basis for developing nanoparticle-based priming strategies for local chili varieties as superior cultivars with optimal growth and seed quality.

METHOD

This study employed a Completely Randomized Design (CRD) consisting of five treatments and five replications. The treatments were variations in *Padina minor* nanoparticle concentrations applied to Kopay chili seeds, namely: no priming (control), hydropriming (water), and nanopriming. Each treatment was applied to one experimental unit and replicated five times. This design enabled a randomized comparison of treatment effectiveness while minimizing the influence of environmental variation on the experimental results. The study was conducted at the Plant Physiology Laboratory, Department of Biology, Faculty of Mathematics and Natural Sciences; the Biota Sumatra Laboratory; and the Central Laboratory of Andalas University, Padang, West Sumatra, Indonesia.

The variables examined in this study included independent, dependent, and controlled variables. The independent variable was the concentration of *Padina minor* nanoparticles (100, 150, and 200 ppm). The dependent variables included time to germination, germination potential, vigor index, root length, shoot length, and catalase and amylase enzyme activities. The controlled variable was the type of Kopay chili seed used, to ensure uniformity of the initial experimental conditions.

Tools and Materials

The equipment used in this study included collection bags, masks, gloves, a blender, an analytical balance, graduated cylinders, beakers, plastic boxes, a sprayer, filter paper (Whatman No. 1), stationery, a camera, an oven, 3% sulfosalicylic acid, ninhydrin reagent, cotton, a water-bath shaker, pots, microtubes, test tubes, tissue paper, labels, polybags, and a spectrophotometer. The materials used were *P. minor*, chili seeds, water, soil, distilled water, glacial acetic acid, phosphoric acid, toluene, and 80% acetone.

Experimental Design

The experiment was arranged in a Completely Randomized Design (CRD) with five treatments and five replications:

A) no priming,
B) hydropriming,
C) *P. minor* nanoparticles at 100 ppm,
D) *P. minor* nanoparticles at 150 ppm, and
E) *P. minor* nanoparticles at 200 ppm.

Research Procedure

The study began with the collection of *Padina minor* seaweed from Nirwana Beach, Padang. The collected samples were manually cleaned of debris, sand, and other organisms under running water to remove adhering foreign particles. The samples were then rinsed with distilled water until all residual salts were dissolved and no residue remained on the surface. After cleaning, the samples were first air-dried in the shade for several hours to reduce their initial moisture content. Drying was then continued until a low moisture level was achieved to ensure material stability prior to grinding. The dried samples were ground using a blender to obtain a coarse powder, which was subsequently processed into nanopowder at PT Nanotech Herbal Indonesia. This process involved particle-size reduction to the nanoscale in order to increase surface area and enhance the bioactivity of the active compounds in the seaweed.

Liquid extract of *P. minor* was prepared by dissolving 0.4 g of nanopowder in 200 mL of sterile distilled water, followed by homogenization using a magnetic stirrer until evenly dissolved. This stock solution was subsequently diluted to obtain treatment concentrations of 100, 150, and 200 ppm, in accordance with the experimental design. All solutions were prepared under sterile conditions to prevent contamination during the priming process.

The chili seeds used in this study were first selected based on size and shape uniformity to ensure relatively homogeneous viability. The seeds were then soaked in each treatment solution (no priming, hydropriming, and nanopriming at the respective concentrations) for 24 h at room temperature. After soaking, the seeds were drained and air-dried for 12 h at room temperature until surface moisture returned to normal before sowing.

Germination was carried out using the towel paper method. Kopay chili seeds (*Capsicum annuum* L.) were used in this study and were obtained from the seed producer PT XYZ, Lot B123, with a seed age of 12 months. Prior to use, the seeds were subjected to preliminary testing to confirm viability and surface moisture status, so that only seeds meeting the required quality standards were used in the experiment. Seed selection was conducted objectively using the following criteria: intact seeds, no physical damage, uniform size, and absence of symptoms of infection or disease. The seeds were arranged evenly in plastic containers lined with several layers of sterile tissue paper moistened with distilled water to achieve a moist but not waterlogged condition. Each container contained 10 chili seeds. The containers were then covered to maintain humidity and placed at laboratory room temperature under controlled lighting conditions. Observations were conducted daily for 10 days after sowing. The filter paper was maintained in a moist condition by adding distilled water as needed using a sprayer to preserve optimal germination conditions.

The physiological parameters observed in this study included time to germination, germination percentage, germination potential, vigor index, root length, and shoot length. Root and shoot lengths were measured using a ruler at the end of the observation period. All data obtained were recorded and analyzed according to the predetermined statistical procedures.

Statistical Analysis

Data for all parameters were analyzed quantitatively and presented as mean ± standard deviation. Prior to analysis, tests of normality (Shapiro-Wilk) and homogeneity of variance (Levene’s test) were performed at a significance level of 5% ($\alpha = 0.05$). Normally distributed data were analyzed using one-way analysis of variance (ANOVA) based on the Completely Randomized Design (CRD), and when significant differences were detected ($p < 0.05$), Duncan’s Multiple Range Test (DMRT) was applied at the 5% level. If the data were not normally distributed, data transformation was performed or the data were analyzed using the non-parametric Kruskal-Wallis test. All statistical analyses were carried out using IBM SPSS Statistics version 25.

RESULTS AND DISCUSSION

Time to Germination Emergence

The results of the study on the effect of varying concentrations of *P. minor* nanoparticle treatment on the time to germination emergence of Kopay chili pepper seeds (*Capsicum annuum* L. cv. Kopay) are presented in Figure 1.

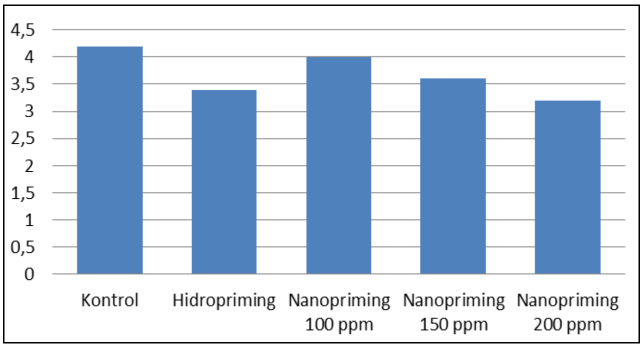

Figure 1. Mean time to germination emergence

The results showed that *Padina minor* nanopriming was able to modify the initial time of seedling emergence in Kopay chili pepper seeds, although the response did not increase consistently with increasing concentration. Seeds without priming exhibited the slowest germination emergence, whereas all priming treatments, both hydropriming and nanopriming, tended to accelerate radicle emergence. This finding indicates that controlled imbibition can optimize early metabolic activation, membrane hydration, and reserve mobilization. Based on Figure 1, nanopriming at 100 ppm and 150 ppm did not differ significantly from hydropriming, whereas the 200 ppm treatment tended to accelerate emergence time, although statistically it remained within the same group. This suggests that the effect of nanopriming on this parameter was moderate and followed a dose-response pattern characteristic of nanoparticles. Mahakham et al. (2016), working with maize seeds, similarly reported that variations in AuNP concentration did not alter the time to germination emergence but did improve other vigor-related traits, indicating that individual germination parameters may respond differently to nanopriming.

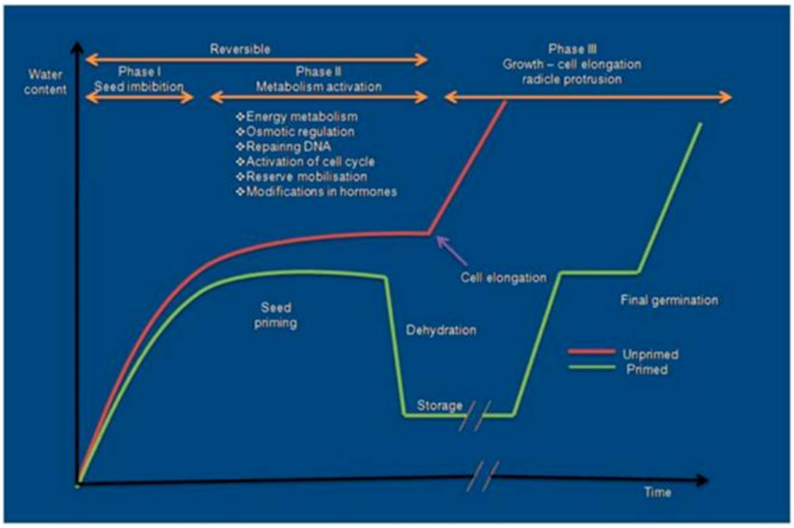

Figure 2. Water uptake curve in primed and non-primed seeds and the phases of seed germination. This figure is an illustration of the mechanism adapted from Marthandan et al. (2020).

Padina minor nanoparticles applied through nanopriming were able to influence chili pepper germination by shortening the lag phase. Water imbibition during seed germination consists of three stages: rapid water uptake (phase I), a lag phase in which seed water potential equilibrates with the surrounding environment (phase II), triggering metabolic changes in preparation for radicle protrusion, and radicle emergence accompanied by another phase of rapid water uptake (phase III) (Widiastuti & Wahyuni, 2020). Primed seeds had already undergone most of phase II during the priming process, consistent with Marthandan et al. (2020), who stated that priming activates pre-germinative metabolic and biochemical processes without radicle protrusion during phase II (Figure 2).

Germination Potential and Vigor Index

Analysis of variance showed that nanopriming with *Padina minor* nanoparticles at different concentrations did not produce significant differences in germination potential or vigor index in Kopay chili pepper. The mean values of germination potential and vigor index are presented in Table 1.

Table 1. Mean germination potential and vigor index of Kopay chili pepper seedlings (*Capsicum annuum* L.) after nanopriming with *Padina minor* nanoparticles at different concentrations.

***Padina minor* nanopriming concentration**	**Germination potential (%)**	**Vigor index (%)**
A (without priming)	98 ± 4.47a	90 ± 10a
B (hydropriming)	100 ± 0a	94 ± 8.9a
C (Nanopriming 100 ppm)	100 ± 0a	96 ± 5.4a
D (Nanopriming 150 ppm)	98 ± 4.47a	94 ± 8.9a
E (Nanopriming 200 ppm)	100 ± 0a	93 ± 8.3a

As shown in Table 1, *Padina minor* nanopriming at different concentrations resulted in high germination percentages, ranging from 98% to 100%. Overall, all treatments, including (A) without priming, (B) hydropriming, and nanopriming at (C) 100 ppm, (D) 150 ppm, and (E) 200 ppm, produced relatively uniform germination. This outcome is attributable to the very high initial seed quality, as the baseline germination capacity was already close to the maximum. With initial seed viability already in the range of 98–100%, the opportunity for further improvement through priming became very limited. This condition is known as the ceiling effect, in which additional treatment does not produce significant differences because the seeds are already able to germinate optimally under natural conditions (Ratnaningtyas & Pudjihartati, 2019). Several studies have also shown that priming tends to exert a greater effect on the speed and uniformity of germination than on the total number of seeds that germinate (Farooq et al., 2019).

The high germination percentage across all treatments indicates that the Kopay chili pepper seeds used in this study had excellent initial viability. Under such conditions of high physiological seed quality, priming treatments generally do not significantly enhance final germination percentage, because most seeds are already capable of germinating optimally (Ratnaningtyas & Pudjihartati, 2019). Thus, *Padina minor* nanopriming did not play a major role in increasing the number of germinated seeds, but it may have greater potential to affect the quality of subsequent seedling growth.

This interpretation is supported by the vigor index results, which were also relatively high across all treatments, ranging from 90% to 96%. Although the differences were not statistically significant, there was a tendency toward higher vigor index values in hydropriming (94%) and nanopriming at 100 ppm (96%) compared with the non-primed control (90%). This trend suggests that priming treatments may enhance seedling uniformity and growth strength. Such effects likely occur because primed seeds can activate hydrolytic enzymes involved in mobilizing seed reserves to support embryo growth (Zulueta-Rodríguez et al., 2015).

Anand et al. (2020) reported that mung bean seeds primed with biogenic MgO nanoparticles derived from *Turbinaria ornata* extract (100 mg/L) exhibited a higher vigor index than those subjected to conventional hydropriming. Lewu et al. (2023) also found that the vigor index of sorghum seeds increased with increasing concentrations of *Sargassum polycystum* seaweed extract. Similarly, Mawale et al. (2024) observed that the vigor index of chili pepper seeds increased with increasing Cu nanoparticle concentration. Ochoa-Chaparro et al. (2024) further reported a highly significant difference in the vigor index of jalapeño pepper seedlings under treatment T3 (124-10) mg/L zinc and molybdenum nanoparticles compared with the control.

In addition, Marthandan et al. (2020) stated that primed seeds facilitate uniform germination through enzyme activation, cellular repair mechanisms, protein synthesis, and stronger antioxidant defense mechanisms than non-primed seeds. Likewise, Hussain et al. (2015) reported that seed priming positively affects germination enhancement and uniformity, increases pre-germinative enzyme activation, stimulates metabolite production, repairs damaged DNA, and regulates osmotic processes. Seed vigor reflects the ability of seeds to grow rapidly, normally, and uniformly (Fatikhasari et al., 2022). According to Ahmadi et al. (2023), priming with appropriate priming agents and concentrations can induce physiological and biochemical changes in seeds that improve germination potential and result in faster, more uniform germination.

Root Length and Shoot Length

Statistical analysis of root and shoot length in Kopay chili pepper seedlings showed that nanopriming with *Padina minor* nanoparticles at different concentrations produced significant differences. The mean values of root and shoot length are presented in Table 2.

Table 2. Mean root length and shoot length of Kopay chili pepper seedlings (*Capsicum annuum* L.) after *Padina minor* nanopriming at different concentrations.

***Padina minor* nanopriming concentration**	**Root length**	**Shoot length**
A (without priming)	1.95 ± 0.47a	2.12 ± 1.20b
B (hydropriming)	2.35 ± 0.35b	1.64 ± 0.23a
C (Nanopriming 100 ppm)	2.84 ± 0.36c	1.61 ± 0.13a
D (Nanopriming 150 ppm)	2.34 ± 0.25b	1.60 ± 0.20a
E (Nanopriming 200 ppm)	2.12 ± 0.52ab	1.53 ± 0.16a

Based on Table 2 and Figure 3, *Padina minor* nanopriming exerted differential effects on the root length of Kopay chili pepper seedlings (*Capsicum annuum* L.). The 100 ppm nanopriming treatment (C) produced the greatest root length, reaching 2.84 ± 0.36, and differed significantly from the other treatments according to DMNRT at the 5% significance level. In contrast, the treatment without priming (A) showed the shortest root length, at 1.95 ± 0.47. These results demonstrate that *Padina minor* nanopriming enhanced early root growth in chili pepper seedlings, particularly at a concentration of 100 ppm. The increase in root length at this concentration suggests that nanoparticles derived from *Padina minor* extract can stimulate early physiological processes associated with germination, especially those related to root cell division and elongation.

These findings are consistent with reports indicating that an appropriate nanoparticle concentration can promote plant root growth. Based on nutrient content analysis conducted by Noli et al. (2022), *P. minor* extract contains high levels of nitrogen and phosphorus. The high phosphorus content in *P. minor* extract is thought to stimulate root development. Hernandez-Herrera et al. (2023) also reported that *Padina caulescens* extract contains high total nitrogen levels and can influence root length. Seaweed extracts can enhance the expression of endogenous auxin and cytokinin genes, and auxin acting together with cytokinin accelerates root formation and promotes root development (Tavares et al., 2020). However, Rizwan et al. (2019) reported that high nanoparticle concentrations may disrupt cellular physiological balance through increased oxidative stress.

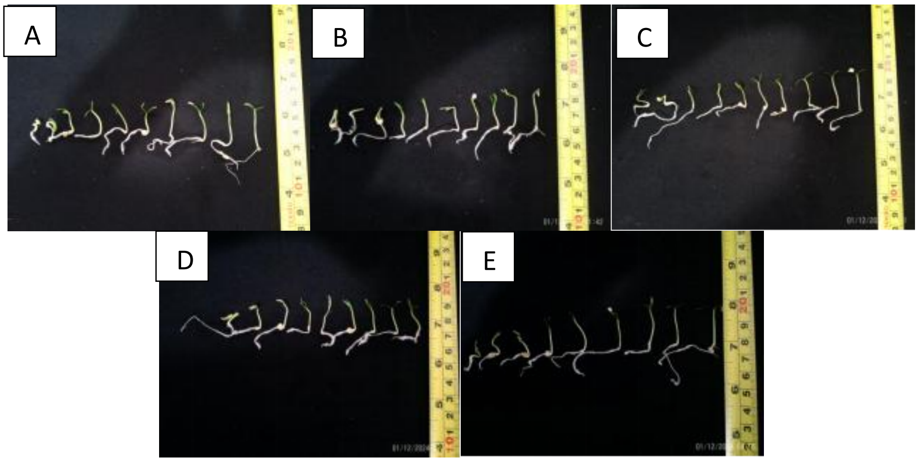

Figure 3. Root length and shoot length of chili pepper seedlings treated with *P. minor* nanoparticle extract at different concentrations: (A) without priming, (B) hydropriming, (C) 100 ppm, (D) 150 ppm, and (E) 200 ppm.

For shoot length, none of the *Padina minor* nanopriming treatments differed significantly from the control. Shoot length ranged from 1.53 ± 0.16 to 2.12 ± 1.20 cm, with the highest value observed in the non-primed treatment and the lowest in the 200 ppm nanopriming treatment. These results indicate that shoot response to nanopriming was not linearly related to increasing concentration.

This pattern may be explained by stimulation at low to moderate concentrations and a decline in benefit at higher concentrations, consistent with the principle of hormesis or a threshold effect. At low to moderate concentrations, bioactive compounds in seaweed extract, including natural hormones such as gibberellins, auxins, cytokinins, kinetin, and zeatin, can stimulate cell proliferation, elongation, and differentiation, thereby promoting shoot growth. Conversely, at higher concentrations, this stimulatory effect may decline because the compounds reach an optimal threshold, reducing or even diminishing the growth-promoting effect on shoots, even though root stimulation may still occur.

The relatively slower shoot response compared with root growth can also be explained physiologically. During the early stages of germination, seed energy allocation is directed primarily toward the establishment of the root system to support water and nutrient uptake before maximal shoot expansion occurs (Taiz et al., 2017). This is consistent with the concept that shoot growth requires greater energy reserves; therefore, changes in shoot length due to priming tend to appear later than changes in root length.

These findings are supported by Bhattacharyya et al. (2015), who reported that active phytochemical compounds in seaweed extracts can simultaneously enhance root and shoot growth. Shayen et al. (2023) further noted that natural hormones in seaweed extracts promote cell proliferation, elongation, and differentiation. In addition, Thriunavukkarasu et al. (2020) reported that *Ulva fasciata* extract at 8% produced the greatest shoot length in chili pepper seedlings, but its benefits declined at higher concentrations, supporting the existence of a threshold effect. A similar result was observed by Ochoa-Chaparro et al. (2024), in which jalapeño seedling shoot length differed significantly at 124–10 mg/L zinc and molybdenum compared with other treatments, again indicating a non-linear response to increasing concentration.

Amylase and Catalase Enzyme Analyses

Statistical analysis showed that different nanopriming treatments did not significantly affect the mean activities of amylase and catalase enzymes. The mean activities of these enzymes in Kopay chili pepper seedlings are presented in Table 3.

Table 3. Mean amylase and catalase enzyme activities of Kopay chili pepper seedlings (*Capsicum annuum* L.) after nanopriming with *Padina minor* nanoparticles at different concentrations.

***Padina minor* nanopriming concentration**	**Amylase enzyme (U/ml)**	**Catalase enzyme (U/ml)**
A (without priming)	39.93 ± 18.96 a	211.23 ± 55.72 a
B (hydropriming)	34.62 ± 11.31 a	204.84 ± 166.49 a
C (Nanopriming 100 ppm)	43.96 ± 14.41 a	199.54 ± 69.65 a
D (Nanopriming 150 ppm)	36.24 ± 2.87 a	115.89 ± 81.67 a
E (Nanopriming 200 ppm)	21.85 ± 4.42 a	118.81 ± 55.70 a

Based on Table 3, the mean amylase activity in Kopay chili pepper seedlings indicates that nanopriming with *Padina minor* nanoparticles produced a response similar to that of the control. This result suggests that nanopriming was not able to enhance either amylase or catalase activity in 3-day-old Kopay chili pepper seedlings compared with the non-primed and hydroprimed treatments. Although controlled water uptake in primed seeds can activate hydrolytic enzymes such as amylase, which is involved in mobilizing stored reserves to support embryo growth (Zulueta-Rodríguez et al., 2015), its effect is highly dependent on plant species and the priming technique used (Marthandan et al., 2020). These results differ from those of Choi et al. (2024), who found that hydropriming increased amylase activity in rice seeds compared with the non-primed control. Priming may increase amylase activity in wheat and rice because both are cereal crops whose stored reserves are dominated by carbohydrates, especially starch. In such species, priming tends to directly and significantly enhance amylase activity to accelerate starch degradation. In contrast, chili pepper seeds may differ in the role and significance of amylase because their primary storage reserves are lipids and proteins rather than starch. This interpretation is consistent with Zou et al. (2015), who reported in a proximate analysis of bird's eye chili seeds that crude fat content was approximately 23–24 g/100 g and crude protein content was approximately 21–22 g/100 g, whereas other fractions were dominated by total dietary fiber at approximately 38 g/100 g. This composition indicates that the major seed reserves are lipids and proteins, while carbohydrates are present largely as fiber rather than as high levels of starch, as in cereals.

The results also showed that nanopriming did not significantly affect catalase activity in Kopay chili pepper seedlings. Catalase functions in detoxifying hydrogen peroxide (H_2O_2), one form of reactive oxygen species (ROS), into water and oxygen, thereby protecting cells from oxidative stress. The absence of significant differences among treatments may be attributed to the relatively optimal germination environment, which did not impose direct drought stress during this stage. Under non-severe stress conditions, ROS production generally remains within the normal physiological range; therefore, the endogenous antioxidant system of the plant, including catalase, may not yet show a marked increase in activity.

Several studies support the view that, during the early germination phase, the plant antioxidant system is still undergoing metabolic adjustment. Paisal et al. (2023) explained that during imbibition and early metabolic activation, increased respiration triggers ROS formation at physiological levels, while antioxidant systems such as catalase and peroxidase develop gradually according to cellular demand. Consequently, antioxidant enzyme activity in the early stage is often fluctuating. Arif and Aloysius (2024) also reported that catalase activity is strongly influenced by stress intensity and exposure duration, with significant increases typically occurring only when plants experience sufficiently strong oxidative stress. In addition, Zhu (2016) stated that nanoparticles can trigger defense responses through a mild stress-signaling mechanism, but this stimulatory effect depends greatly on concentration, particle size, and plant species sensitivity.

Overall, the results indicate that nanopriming with *Padina minor* nanoparticles produced selective effects on the germination parameters of Kopay chili pepper seeds. The treatment most consistently enhanced the speed of germination emergence and early root growth, particularly at a concentration of 100 ppm, whereas other parameters, including shoot length, germination percentage, vigor index, and amylase and catalase enzyme activities, did not differ significantly from the control or hydropriming. This pattern suggests that nanopriming plays a more specific role in accelerating particular physiological processes rather than uniformly improving all aspects of seed viability or seedling quality. Therefore, the effect of nanopriming can be understood as a targeted stimulation of early germination processes, while other parameters remain strongly influenced by the initial physiological quality of the seeds and the surrounding environmental conditions.

CONCLUSION

Nanopriming with *Padina minor* nanoparticles exerted selective effects on the germination and early seedling growth of Kopay chili pepper (*Capsicum annuum* L. cv. Kopay). Among the evaluated parameters, the treatment was most effective in accelerating germination emergence and promoting early root elongation, with the 100ppm concentration showing the most favorable response. In contrast, germination potential, vigor index, shoot length, and the activities of amylase and catalase were not significantly affected compared with the control and hydropriming treatments. These findings indicate that *P. minor*-based nanopriming primarily enhances specific early physiological processes rather than uniformly improving all germination and vigor traits. Overall, the results suggest that 100 ppm is the most promising concentration for improving early seed performance in Kopay chili pepper, particularly in terms of faster emergence and stronger root development. Further studies under field or stress conditions are needed to determine whether these early advantages can be translated into improved plant establishment and subsequent growth performance.

RECOMMENDATION

For future research, it is recommended that the evaluation of *Padina minor* nanopriming in Kopay chili pepper be extended to the vegetative and generative stages, with particular emphasis on drought tolerance. The assessment should include plant growth, fruit yield, capsaicin content, and physiological responses to drought stress. In addition, molecular analysis using qPCR on drought-related genes is recommended to provide deeper insight into the mechanisms underlying plant responses.

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