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# Effectiveness of plant growth regulator fertilizers on the recovery of pepper plants under water stress conditions

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**Abstract:** This study examined the effects of three plant growth regulator fertilizers (Atonick, N3M, and Profarm) on the performance of black pepper (*Piper nigrum*) under various water stress conditions (drought, waterlogging, and control). Conducted in a greenhouse over a two-month period from June to July 2024 using sandy clay-loam soil, the study employed a Randomized Complete Block Design with ten replicates (each plant was used as a replicate) to measure growth parameters, such as plant height, number of leaves, branches, stem diameter, leaf area, fresh weight, and dry weight. Results showed that N3M significantly enhanced growth under drought stress, with plant height reaching 32.99 cm, leaf count 11.78, and dry weight 6.02 g after two weeks, compared to the control's 29.78 cm, 10.33 leaves, and 4.56 g, respectively. These findings confirm N3M's superior efficacy in improving black pepper growth under water stress. Compared to Atonick and Profarm, N3M's balanced macronutrient and micronutrient content, including nitrogen, phosphorus, potassium, and trace elements of plants, played a crucial role in maintaining physiological functions and mitigating the adverse effects of environmental stress. The results suggest that targeted nutrient supplementation, particularly with N3M, can optimize black pepper's resilience under water stress conditions, contributing to better agricultural management practices in the face of climate change. Further research is recommended to explore the long-term impacts of these fertilizers across varying environmental conditions to enhance crop resilience more broadly.

**Keywords:** Black pepper, drought, waterlogging, plant growth regulators, N3M.

## Introduction

Black pepper (*Piper nigrum*), native to the Western Ghats of India (Reshma et al. 2022), is one of the most widely used spices globally and plays a significant role in the economies of tropical countries like Vietnam, the world's largest producer (42% of global pepper production) and exporter (Moreira et al., 2021; Korah and Mohankumar, 2021). However, its cultivation is highly sensitive to climate conditions, with increasing droughts and waterlogging posing serious threats to production (Izzah et al., 2019). In Vietnam, erratic rainfall and prolonged droughts have already led to root damage and yield losses. Drought reduces growth and increases disease susceptibility, while waterlogging causes root rot and other waterborne diseases (Kaur et al., 2020). As these extreme conditions become more frequent due to climate change, it is essential to evaluate their impacts and develop technical solutions such as improved irrigation, soil management, and stress-tolerant varieties to ensure the sustainability of Vietnam's black pepper industry. In addition, using effective fertilizers and soil amendments that enhance drought and waterlogging tolerance is critical in mitigating these stresses, helping to maintain plant health and productivity under adverse conditions.

Water stresses negatively impact black pepper cultivation, with both drought and waterlogging posing serious threats to plant growth and yield (Malhotra, 2017; Long et al., 2024). Drought tolerance in black pepper varies depending on growth stages and environmental factors (Delfine et al., 2001; Farooq et al., 2012), and water shortages can reduce crop yields by up to 70% (Dinar et al., 2019). Typically grown in regions with uneven rainfall, black pepper often faces severe water shortages during dry seasons (Pallavi and Abida, 2018). Drought-tolerant varieties exhibit higher water retention and lower cell membrane permeability (George et al., 2017), with mechanisms such as stomatal regulation, leaf water movement, and root penetration contributing to their resilience (Vasantha et al., 1990). However, while recent studies show increased water-use efficiency and reduced stomatal conductance under drought conditions, black pepper struggles to recover vegetative growth after rehydration, indicating limitations in long-term drought resilience (Ferreira et al., 2024). In contrast, waterlogging reduces dissolved oxygen, leading to hypoxia and limiting aerobic respiration in roots (Blom and Voesenek, 1996). Roots then shift to anaerobic respiration, producing by-products like ethanol, which inhibit growth in susceptible plants (Drew, 1997; Yin et al., 2013). While some crops adapt through morphological changes such as adventitious root formation and gas-filled tissues for oxygen transport (Daniel and Hartman, 2024; Justin and Armstrong, 1987), black pepper roots are particularly sensitive to waterlogging and show minimal resistance (Ton et al., 2008; Long et al., 2024). Since the root system is closely linked to the above-ground parts of the plant, any stress affecting the roots will ultimately influence overall plant growth, including leaf development, photosynthetic capacity, and fruit yield. Thus, the response of roots to water stresses is crucial for maintaining the vigor of black pepper plants, as root health directly impacts the plant's ability to absorb nutrients and water, sustain photosynthesis, and produce fruit. To facilitate recovery after periods of stress, it is essential to use root fertilizers that enhance root growth and improve nutrient absorption, allowing the plant to regain its vigor and productivity more efficiently.

Numerous studies have focused on regulator fertilizers to enhance crops' recovery capacity, particularly their root systems (Fageria and Moreira, 2011). For example, Atonik, $N_3M$, and Profarm regulator fertilizers have proven to enhance plant growth and resilience under drought and waterlogged conditions due to their distinct formulations and mechanisms of action (Covasa et al., 2023; Przybysz et al., 2014). Atonik contains plant growth regulators, such as Sodium-5-Nitroguaiacolate, Sodium-O-Nitrophenolate, and Sodium-P-Nitrophenolate, which stimulate cell division, root development, and photosynthesis (Batool et al., 2023). These PGRs significantly improve root architecture, enhancing water absorption during drought. At the same time, under waterlogged conditions, they promote the formation of aerenchyma tissues that aid in oxygen transport to roots, helping crops tolerate hypoxia (Chen and Dong, 2016; Noreem et al., 2020). N3M, on the other hand, combines a balanced mix of macronutrients, including nitrogen (11%), phosphorus (3%), potassium (2.5%), and vital micronutrients such as boron, zinc, and manganese. Nitrogen supports leaf production and photosynthesis, phosphorus aids in deep root growth, and potassium regulates water loss by controlling stomatal function, making crops like maize, rice, and potato more drought-resilient by enabling deeper soil moisture access. Under waterlogged conditions, N3M-treated plants exhibit sustained root activity and higher photosynthetic efficiency, preserving yields. Profarm stands out for its high P content (52%), along with N (8%) and P (17%), which boost root development and enhance water uptake. Its rich micronutrient content further aids in osmotic balance and recovery from waterlogging stress by improving root oxygenation and nutrient availability. In crops such as corn, sunflower, and sorghum, Profarm has been shown to improve drought resilience by increasing root mass and enhancing flowering and seed set under stress conditions. Together, these fertilizers work synergistically to improve root development, nutrient uptake, and photosynthetic performance, enabling various crops to survive, grow, and yield better under drought and waterlogged environments. This research aims to evaluate these fertilizers' effectiveness in restoring root vigor following water stress conditions.

## Results

### *Effects of regulator fertilizers on the plant height of black pepper under water stresses*

After one and two weeks of applying the regulator fertilizers, clear trends were observed in plant height under different conditions (Table 1). N3M consistently resulted in the tallest plants across all conditions, with drought conditions showing the highest growth at 23.59 cm after one week and 32.99 cm after two weeks. In contrast, control consistently produced the shortest plants, with 18.53 cm after one week and 29.78 cm after two weeks in drought conditions. Antonik and Profarm treatments showed no significant differences but consistently performed better than water. N3M again led with the greatest height in waterlogging conditions, while water showed the least growth. Under control conditions, N3M remained the most effective, producing significantly taller plants than other treatments.

### *Effects of regulator fertilizers on the number of leaves of black pepper under water stresses*

The results in Table 2 reveal how different treatments affected the number of leaves under drought, waterlogging, and control conditions. After one week under control conditions, N3M produced the highest leaf count (11.33), significantly greater than all other treatments, while water had the lowest (9.11). After two weeks, N3M still led with 12.78 leaves, followed closely by Antonik (12.67), both significantly higher than water (10.00) and Profarm (11.00). In drought conditions, N3M also showed the best performance after one week with 10.22 leaves, significantly higher than Profarm (9.00), while water (9.44) and Antonik (9.89) were intermediate. After two weeks, N3M again had the highest number of leaves (11.78), significantly differing from water (10.33) and Profarm (10.22), though Antonik (11.11) performed similarly. Under waterlogging conditions, water consistently produced the lowest number of leaves, with 7.67 after one week and 8.89 after two weeks, significantly lower than all other treatments. N3M and Antonik performed similarly, with both reaching 10.67 leaves after two weeks, while Profarm remained intermediate.

**Table 1.** Effects of regulator fertilizers on the plant height of black pepper under water stresses.

| Conditions | Treatments | Plant height (cm) | |
|---|---|---|---|
| | | One week after treatment | Two weeks after treatment |
| Control | Water | 22.56$^{a}$ | 32.57$^{bc}$ |
| | Antonik | 22.78$^{a}$ | 33.52$^{b}$ |
| | N3M | 23.06$^{a}$ | 34.60$^{a}$ |
| | Profarm | 22.86$^{a}$ | 33.24$^{b}$ |
| Drought | Water | 18.53$^{d}$ | 29.78$^{g}$ |
| | Antonik | 20.38$^{bc}$ | 31.82$^{cd}$ |
| | N3M | 23.59$^{a}$ | 32.99$^{b}$ |
| | Profarm | 20.31$^{bc}$ | 30.84$^{ef}$ |
| Waterlogging | Water | 17.36$^{e}$ | 27.90$^{h}$ |
| | Antonik | 19.96$^{c}$ | 31.59$^{de}$ |
| | N3M | 21.29$^{b}$ | 32.61$^{bc}$ |
| | Profarm | 18.74$^{d}$ | 30.00$^{fg}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

**Table 2.** Effects of regulator fertilizers on the number of leaves of black pepper under water stresses.

| Conditions | Treatments | Number of leaves | |
|---|---|---|---|
| | | One week after treatment | Two weeks after treatment |
| Control | Water | 9.11$^{d}$ | 10.00$^{cde}$ |
| | Antonik | 10.89$^{ab}$ | 12.67$^{a}$ |
| | N3M | 11.33$^{a}$ | 12.78$^{a}$ |
| | Profarm | 10.33$^{bc}$ | 11.00$^{bc}$ |
| Drought | Water | 9.44$^{cd}$ | 10.33$^{cd}$ |
| | Antonik | 9.89$^{cd}$ | 11.11$^{bc}$ |
| | N3M | 10.22$^{bc}$ | 11.78$^{ab}$ |
| | Profarm | 9.00$^{de}$ | 10.22$^{cd}$ |
| Waterlogging | Water | 7.67$^{f}$ | 8.89$^{e}$ |
| | Antonik | 9.00$^{de}$ | 10.67$^{bc}$ |
| | N3M | 9.11$^{d}$ | 10.67$^{bc}$ |
| | Profarm | 8.11$^{ef}$ | 9.22$^{de}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

***Effects of regulator fertilizers on the number of branches of black pepper under water stresses***

The results presented in Table 3 highlight the effects of different treatments on the branch growth of pepper plants under drought, waterlogging, and control conditions. After one week in drought conditions, the N3M treatment led to 2.33 branches per plant, significantly surpassing water (1.78) and Profarm (1.78), while Antonik (2.56) also performed well but did not significantly differ from N3M. In waterlogging conditions, N3M again demonstrated superiority with 2.33 branches, significantly higher than the other treatments. Under control conditions, N3M achieved the highest branch count of 3.22, significantly differing from all other treatments, with Antonik following closely at 2.89. After two weeks, N3M continued to excel, reaching 3.44 branches under drought conditions and 2.78 under waterlogging conditions, significantly higher than other treatments. N3M reached 4.44 branches in control conditions, significantly outperforming Antonik (3.33) and the other treatments.

***Effects of regulator fertilizers on the stem diameter of black pepper under water stresses***

The results in Table 4 show the impact of different treatments on the stem diameter of black pepper plants. After one week of drought, N3M had the highest stem diameter at 6.21 mm, significantly greater than other treatments. The water treatment had the lowest diameter at 5.79 mm, significantly different from N3M and Antonik (6.05 mm) but not from Profarm (5.85 mm). In waterlogged conditions, water recorded the lowest diameter at 5.27 mm, significantly differing from all other treatments, while N3M had the highest at 5.68 mm. Antonik (5.50 mm) and Profarm (5.52 mm) showed no significant difference. In control conditions, N3M (6.29 mm) and Antonik (6.22 mm) had the highest diameters, significantly differing from water (5.92 mm) and Profarm (6.03 mm). After two weeks of drought, N3M again led with 6.42 mm, significantly different from water's lowest value of 6.00 mm. Antonik (6.31 mm) and Profarm (6.22 mm) also showed significant differences. In waterlogging conditions, the lowest diameter was with water at 5.58 mm, while N3M had the highest at 5.92 mm, significantly different from others. N3M reached 6.49 mm in control conditions, while Antonik and Profarm had 6.38 mm and 6.30 mm, respectively. water recorded the lowest at 6.28 mm, significantly different from all treatments. In summary, N3M consistently showed the highest stem diameter across all conditions, while water exhibited the lowest, especially. In waterlogging conditions, it is indicated to have poorer efficacy. Antonik and Profarm

**Table 3.** Effects of regulator fertilizers on the number of branches of black pepper under water stresses.

| Conditions | Treatments | Number of branches | |
|---|---|---|---|
| | | One week after treatment | Two weeks after treatment |
| Control | Water | 1.78$^{c}$ | 2.56$^{bcd}$ |
| | Antonik | 2.89$^{ab}$ | 3.33$^{bc}$ |
| | N3M | 3.22$^{a}$ | 4.44$^{a}$ |
| | Profarm | 2.00$^{bc}$ | 2.67$^{bcd}$ |
| Drought | Water | 1.78$^{c}$ | 2.33$^{cd}$ |
| | Antonik | 2.56$^{abc}$ | 2.56$^{bcd}$ |
| | N3M | 2.33$^{abc}$ | 3.44$^{ab}$ |
| | Profarm | 1.78$^{c}$ | 1.89$^{d}$ |
| Waterlogging | Water | 1.67$^{c}$ | 2.00$^{d}$ |
| | Antonik | 1.89$^{c}$ | 2.22$^{d}$ |
| | N3M | 2.33$^{abc}$ | 2.78$^{bcd}$ |
| | Profarm | 1.67$^{c}$ | 2.33$^{cd}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

**Table 4.** Effects of regulator fertilizers on the stem diameter of black pepper under water stresses.

| Conditions | Treatments | Stem diameter (mm) | |
|---|---|---|---|
| | | One week after treatment | Two weeks after treatment |
| Control | Water | 5.92$^{bc}$ | 6.28$^{cd}$ |
| | Antonik | 6.22$^{a}$ | 6.38$^{abc}$ |
| | N3M | 6.29$^{a}$ | 6.49$^{a}$ |
| | Profarm | 6.03$^{b}$ | 6.30$^{bcd}$ |
| Drought | WATER | 5.79$^{cd}$ | 6.00$^{e}$ |
| | Antonik | 6.05$^{b}$ | 6.31$^{bcd}$ |
| | N3M | 6.21$^{a}$ | 6.42$^{ab}$ |
| | Profarm | 5.85$^{c}$ | 6.22$^{d}$ |
| Waterlogging | Water | 5.27$^{f}$ | 5.58$^{h}$ |
| | Antonik | 5.50$^{e}$ | 5.79$^{fg}$ |
| | N3M | 5.68$^{d}$ | 5.92$^{ef}$ |
| | Profarm | 5.52$^{e}$ | 5.76$^{g}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

provided intermediate results in promoting stem diameter growth.

***Effects of regulator fertilizers on the leaf area of black pepper under water stresses***

After one week, the N3M treatment under drought conditions achieved the highest leaf area at 130.09 cm$^2$, significantly differing from Profarm (114.87 cm$^2$) and water (95.79 cm$^2$), which had the lowest values. Under waterlogging conditions, N3M maintained the highest leaf area at 130.37 cm$^2$, significantly different from Antonik (115.21 cm$^2$), Profarm (109.90 cm$^2$), and water (91.71 cm$^2$). In control conditions, N3M recorded a leaf area of 144.48 cm$^2$, again significantly higher than all other treatments. After two weeks, N3M demonstrated superior leaf area across all conditions, achieving 150.28 cm$^2$ under waterlogging conditions and 164.53 cm$^2$ in control conditions, while water consistently exhibited the lowest values, indicating less effective performance.

***Effects of regulator fertilizers on the fresh weight of black pepper plants under water stresses***

Results from Table 6 reveal the impact of various treatments on the fresh weight of black pepper plants under stress conditions. After one week in drought conditions, the N3M treatment exhibited the highest fresh weight at 17.23 g, significantly differing from water (12.14 g), Profarm (13.98 g), and Antonik (15.96 g), with water showing the lowest weight. In waterlogging conditions, N3M again led with a fresh weight of 13.84 g, comparable to Antonik (12.75 g), while water had the lowest at 10.38 g. Under control conditions, N3M reached 20.67 g, significantly higher than Antonik (18.96 g), Profarm (16.73 g), and water (15.76 g). After two weeks, in Limited Conditions, N3M continued to show the highest fresh weight at 19.77 g, followed by Antonik (18.55 g), Profarm (16.47 g), and the lowest in water (14.53 g). In waterlogging conditions, N3M maintained the highest weight at 16.32 g, although not significantly different from Antonik (15.24 g). In control conditions, N3M achieved 23.11 g, significantly outpacing Antonik (21.46 g), Profarm (19.21 g), and water (18.26 g). Overall, the findings indicate that stress factors like drought and waterlogging conditions adversely affect fresh weight, with N3M consistently demonstrating superior results across all conditions. At the same time, Profarm and water exhibited lower weights, especially water, which consistently showed the least effectiveness.

**Table 5.** Effects of regulator fertilizers on the leaf area of black pepper under water stresses.

| Conditions | Treatments | Leaf area ($cm^2$ $plant^{-1}$) | |
|---|---|---|---|
| | | One week after treatment | Two weeks after treatment |
| Control | Water | 104.18$^{fg}$ | 143.14$^{cd}$ |
| | Antonik | 119.58$^{d}$ | 149.56$^{bc}$ |
| | N3M | 144.48$^{a}$ | 164.53$^{a}$ |
| | Profarm | 109.10$^{ef}$ | 150.83$^{bc}$ |
| Drought | Water | 95.79$^{gh}$ | 129.01$^{ef}$ |
| | Antonik | 121.03$^{cd}$ | 148.12$^{bc}$ |
| | N3M | 130.09$^{bc}$ | 152.82$^{b}$ |
| | Profarm | 114.87$^{de}$ | 141.89$^{cd}$ |
| Waterlogging | Water | 91.71$^{h}$ | 121.21$^{f}$ |
| | Antonik | 115.21$^{de}$ | 136.36$^{de}$ |
| | N3M | 130.37$^{b}$ | 150.28$^{bc}$ |
| | Profarm | 109.90$^{ef}$ | 134.03$^{de}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

**Table 6.** Effects of regulator fertilizers on the fresh weight of black pepper under water stresses.

| Conditions | Treatments | Fresh weight (g $plant^{-1}$) | |
|---|---|---|---|
| | | One week after treatment | Two weeks after treatment |
| Control | Water | 15.76$^{d}$ | 18.26$^{e}$ |
| | Antonik | 18.96$^{b}$ | 21.46$^{b}$ |
| | N3M | 20.67$^{a}$ | 23.11$^{a}$ |
| | Profarm | 16.73$^{c}$ | 19.21$^{d}$ |
| Drought | WATER | 12.14$^{fg}$ | 14.53$^{h}$ |
| | Antonik | 15.96$^{d}$ | 18.55$^{e}$ |
| | N3M | 17.23$^{c}$ | 19.77$^{c}$ |
| | Profarm | 13.98$^{e}$ | 16.47$^{f}$ |
| Waterlogging | Water | 10.38$^{h}$ | 12.72$^{i}$ |
| | Antonik | 12.75$^{f}$ | 15.24$^{g}$ |
| | N3M | 13.84$^{e}$ | 16.32$^{f}$ |
| | Profarm | 11.60$^{g}$ | 14.11$^{h}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

***Effects of regulator fertilizers on the dry weight of black pepper under water stresses***

The findings from Table 7 indicate significant differences among the treatments under various stress conditions. After one week, under drought conditions, the N3M treatment yielded the highest dry weight at 5.46 g, significantly different from Antonik (4.91 g), Profarm (4.23 g), and the lowest, water treatment (3.73 g). In waterlogging conditions, N3M again had the highest value at 4.21 g, although it was not statistically different from Antonik (3.92 g) and Profarm (3.60 g), while water (3.18 g) remained the lowest. Under control conditions, N3M reached 6.62 g, significantly higher than all other treatments, with Antonik at 5.79 g, Profarm at 5.25 g, and water at 4.83 g. After two weeks, N3M continued to show superiority with 6.02 g under drought conditions, significantly different from Antonik (5.60 g), Profarm (5.16 g), and water (4.56 g). In waterlogging conditions, N3M again led with 5.06 g, significantly outperforming the others, while water (3.98 g) exhibited the lowest value. Under well-water condition, N3M achieved the highest dry weight of 7.18 g, followed by Antonik (6.53 g), Profarm (6.06 g), and the lowest being water (5.50 g), which was significantly different from the others.

**Discussion**

Drought and waterlogging are both major challenges for black pepper cultivation, but waterlogging presents a greater threat due to the plant's limited capacity to adapt. Drought, particularly in regions with uneven rainfall, can reduce black pepper yields by up to 70% (Dinar et al., 2019), depending on growth stages and environmental factors (Delfine et al., 2001; Farooq et al., 2012). Drought-tolerant varieties exhibit mechanisms like higher water retention, stomatal regulation, and deeper root penetration (George et al., 2017; Vasantha et al., 1990), yet black pepper struggles to regain vegetative growth after rehydration, highlighting its limitations in long-term drought resilience (Ferreira et al., 2024). Waterlogging, however, causes hypoxia in the soil, forcing roots into anaerobic respiration, producing harmful by-products like ethanol, which inhibit growth (Blom and Voesenek, 1996; Drew, 1997; Yin et al., 2013). While some plants adapt by developing adventitious roots or gas-filled tissues (Daniel and Hartman, 2024; Justin and Armstrong, 1987), black pepper exhibits minimal resistance to these conditions (Ton et al., 2008; Long et al., 2024). This study supports these findings, showing that drought and waterlogging negatively affect growth parameters such as plant height, leaf number, stem diameter, and leaf area. However, waterlogging has a more severe impact on overall plant health and productivity.

In this study, we mainly focused on evaluating the effects of three distinct plant additives, including Atonik, N3M, and Profarm, on enhancing the abiotic stress tolerance of black pepper plants under drought and waterlogging conditions. These additives were analyzed for their impact on various growth parameters, including plant height, leaf number per plant, branch number per plant, stem diameter, leaf area, fresh weight, and dry weight. Each of these parameters is believed to be critical for understanding how well black pepper plants can cope with environmental stressors (Negi et al., 2021; Ou et al., 2011 ). Firstly, Atonik, containing nitroguaiacolate and nitrophenolate compounds, is known for promoting plant growth and enhancing stress resistance (Covasa et al., 2023; Przybysz et al., 2014). For example, the application of the Atonik biostimulant has been shown to enhance salt stress tolerance in tomato cultivars by positively influencing various physiological and biochemical processes (Covasa et al., 2023). Under salt stress conditions, Atonik stimulated stem growth, increased the number of flowers, and improved fruit production in the studied tomato varieties. It also enhanced chlorophyll a and b concentrations, improving photosynthetic capacity, which is crucial for plant adaptation under salinity stress. Furthermore, Atonik increased proline accumulation, an important osmoprotectant that aids in stress tolerance by stabilizing proteins and membranes. This combination of improved growth, photosynthesis, and osmotic regulation contributed to tomato plants' increased salt stress tolerance, allowing them to better cope with the ionic and osmotic imbalances caused by saline environments (Covasa et al., 2023). In this study, Atonik demonstrated a significant positive effect on the growth of black pepper plants, particularly in improving plant height and leaf number per plant. The presence of sodium salts of nitrophenolates likely contributed to improved nutrient uptake and physiological processes under stress conditions, allowing the plants to grow better despite adverse environments. These results align with previous findings, where nitrophenolates have been associated with enhanced root and shoot development, especially under stress conditions. Secondly, N3M, which includes a blend of essential macronutrients (N, P, K) and trace elements (B, Cu, Zn, Mn, Fe), effectively improved the overall structural growth of the black pepper plants (Su et al., 2024). The nutrient-rich formulation provided a balanced supply of essential elements that are critical in stress resilience. Nitrogen is vital for vegetative growth, phosphorus for energy transfer and root development, and potassium for regulating osmotic balance, which is crucial under drought or waterlogging. The trace elements further improved plant metabolic processes, ensuring continued growth under stressful conditions. N3M-treated plants increased stem diameter, branch number, and fresh and dry weights, suggesting that the formulation supported both above-ground biomass accumulation and root stability. Finally, Profarm, a high-phosphorus additive with significant concentrations of micronutrients like Fe, Zn, Mg, Cu, and Bo, had a pronounced effect on the leaf area and overall biomass of the plants. Phosphorus is essential for root growth and energy transfer, and its abundance in Profarm likely contributed to better water and nutrient absorption, thus enhancing tolerance to stress. Additionally, the micronutrients in Profarm played a role in improving photosynthesis and enzymatic activities, leading to higher biomass production even under suboptimal conditions. The observed increase in leaf area and weight indicates that Profarm promoted growth and supported physiological functions vital for stress adaptation. Collectively, the application of these additives demonstrated their potential to enhance the growth and stress tolerance of black pepper plants. Each additive contributed uniquely to different aspects of plant development, emphasizing the importance of a multifaceted approach to managing environmental stress in agriculture. The findings from this study provide valuable insights into how specific nutrient and growth stimulant formulations can be used to improve crop resilience, which is particularly relevant in the context of climate change and increasing agricultural challenges. Further studies should investigate the long-term effects of these additives and explore their interactions with different soil types and environmental conditions to optimize their use in black pepper cultivation.

In this study, N3M treatment shows higher effectiveness under both drought and waterlogging conditions compared to Atonik and Profarm due to its comprehensive nutrient composition and special formulation, which directly addresses the physiological challenges posed by extreme environmental stresses. Unlike Atonik, which is primarily a biostimulant containing nitrophenolate compounds that enhance plant growth and stress tolerance by stimulating specific biochemical pathways, N3M provides a broader range of essential macronutrients and micronutrients, which are critical for maintaining overall plant health and development during stress (Su et al., 2024). This nutrient-rich composition allows N3M to support both immediate stress responses and long-term plant resilience, making it more versatile in coping with diverse stress conditions such as drought and waterlogging conditions (Kohv et al., 2023; Su et al., 2024). Under drought conditions, N3M's high nitrogen content enhances vegetative growth and protein synthesis. At the same time, potassium plays a key role in regulating stomatal opening and closing, which helps the plant maintain water balance by controlling transpiration. This osmotic regulation is critical during periods of water scarcity. Phosphorus supports root growth, enabling plants to access deeper water sources, thus improving drought tolerance. The micronutrients in N3M, particularly zinc and manganese, also support enzymatic activities that improve water uptake efficiency and mitigate oxidative damage caused by drought-induced stress. In contrast, Atonik's action focuses more on stimulating growth and recovery rather than providing the comprehensive nutrient support required to maintain cellular functions under prolonged stress. In waterlogging conditions, N3M proves to be more effective than Profarm because it supports energy transfer and root development through phosphorus but also aids in recovering from the oxygen-deficient environment that characterizes waterlogged soils. Potassium and other

**Table 7.** Effects of regulator fertilizers on the dry weight of black pepper under water stresses.

| Conditions | Treatments | Dry weight (g plant$^{-1}$) One week after treatment | Two weeks after treatment |
|---|---|---|---|
| Control | Water | 4.83$^{e}$ | 5.50$^{de}$ |
| | Antonik | 5.79$^{b}$ | 6.53$^{b}$ |
| | N3M | 6.62$^{a}$ | 7.18$^{a}$ |
| | Profarm | 5.25$^{cd}$ | 6.06$^{c}$ |
| Drought | Water | 3.73$^{g}$ | 4.56$^{g}$ |
| | Antonik | 4.91$^{de}$ | 5.60$^{d}$ |
| | N3M | 5.46$^{bc}$ | 6.02$^{c}$ |
| | Profarm | 4.23$^{f}$ | 5.16$^{ef}$ |
| Waterlogging | Water | 3.18$^{h}$ | 3.98$^{h}$ |
| | Antonik | 3.92$^{fg}$ | 4.58$^{g}$ |
| | N3M | 4.21$^{f}$ | 5.06$^{f}$ |
| | Profarm | 3.60$^{g}$ | 4.36$^{gh}$ |

Different letters within the same column indicate statistically significant differences at the $P < 0.05$ level.

micronutrients in N3M help alleviate the negative impacts of waterlogging by improving the plant's ability to regulate ionic balance and recover from anaerobic conditions. Although Profarm, which is high in phosphorus and micronutrients, provides some benefits by enhancing root strength and nutrient absorption, it lacks the balanced nitrogen and potassium content that is critical for managing osmotic stress and maintaining physiological processes during waterlogging. N3M's inclusion of special additives also differentiates it from Atonik and Profarm in terms of its stress tolerance enhancement capabilities. These additives likely include compounds that act as osmoprotectants, antioxidants, or other stress-mitigating agents, which help plants maintain cellular homeostasis during extreme environmental fluctuations. By addressing nutrient deficiencies and stress responses, N3M provides a more holistic approach to plant care under adverse conditions. In contrast, Atonik primarily stimulates growth processes, and Profarm focuses on nutrient supply without specifically enhancing the plant's ability to regulate water and nutrient uptake under stress. Therefore, N3M's broader spectrum of action makes it the most effective treatment for improving plant resilience in both drought and waterlogging scenarios.

## Materials and Methods

### *Plant material*

The Vinh Linh black pepper variety, widely cultivated in Vinh Linh district, Quang Tri province, Vietnam, was used in this study. This variety is famous for its distinctive flavor and high quality, which are attributed to the region's unique climate and soil conditions.

### *Experimental design*

The experiment was conducted in a greenhouse at the Faculty of Agronomy, Vietnam National University of Agriculture, with an average light intensity of 1150 µmol $m^2$ $s^{-1}$. Sandy clay-loam soil, composed of 56% sand, 23% silt, 20% clay, and 1% humus, was sieved through a 10-mm mesh screen before use. Uniform pepper cuttings, each 30 cm in shoot length, were planted in plastic pots (320 mm bottom diameter, 400 mm top diameter, and 320 mm height), each filled with 15 kg of dried sandy clay-loam soil and fertilized with 0.81 g N, 0.54 g $P_2O_5$, and 0.54 g $K_2O$. After 21 days, three water regimes—well-irrigated (control), waterlogging, and drought—were applied for 10 days, where the control group maintained 30% soil moisture, the waterlogged group experienced saturated conditions, and the drought-stressed group received no water. Each treatment group consisted of 36 pots. After the 10-day treatment period, plants were divided into four groups for recovery regulator fertilization: control conditions (Control 1 and Control 2 refer to plants that are well-watered but not fertilized following drought and waterlogging stresses, respectively, Antonik, N3M, or Profarm. Atonick contains Sodium-5-Nitroguaiacolate (3g/l), Sodium-O-Nitrophenolate (6g/l), and Sodium-P-Nitrophenolate (9g/l). N3M provides a balanced blend of essential macronutrients, including N (11%), $P_2O_5$ (3%), $K_2O$ (2.5%), along with micronutrients like Bo (0.02%), Cu, Zn, Mg, and Fe (each 0.2%), and special additives. Profarm is a high-nutrient fertilizer with Nitrogen (8%), $P_2O_5$ (52%), $K_2O$ (17%), and trace elements such as Fe (200 ppm), Zn (100 ppm), Mg (100 ppm), Cu (100 ppm), Bo (120 ppm), and 5% moisture. These three fertilizers were applied at a rate of 10 g mixed with 16 liters of water, then used to water the plants in the experimental treatments until the soil reached saturation. The 12 experimental factors were laid out in a Randomized Complete Block Design with ten replicates.

### *Measurements*

Experimental samples were collected twice, at the end of the first week and the second week after applying the regulator fertilizers. The evaluated traits included plant height (PH), number of leaves (NoL), number of branches (NoB), leaf area (LA), fresh weight (FW), and dry weight (DW). PH was measured from the soil surface to the top of the main stem. NoL was counted using 1 cm of length and the presence of the axillary bud as the threshold, while NoB was determined based on lateral shoots reaching approximately 1 cm in length. LA was calculated using a leaf area meter (Li-3100, Lincoln, Nebraska, USA), and FW was measured with an electronic balance (OHAUS PR4202, USA). DW was assessed after drying the samples at 80 °C for three days in a drying chamber (BINDER, USA) until a constant weight was achieved.

***Data analysis***

Analysis of variance (ANOVA) was performed to analyze the effects of treatments using R (R Core Team, 2021). Means compared using LSD at a 5% significance level in the case of the significance of the impact of treatments on the measured variable.

## Conclusion

This study investigated the effects of three plant growth regulator fertilizers, including Atonik, N3M, and Profarm, on the recovery and performance of black pepper under drought and waterlogging stress conditions. The results demonstrated that the application of N3M fertilizer significantly enhanced growth parameters, such as plant height, leaf number, branch number, stem diameter, leaf area, and both fresh and dry weight, particularly under drought stress. N3M's balanced composition of macronutrients and micronutrients contributed to improved drought and waterlogging tolerance, surpassing the effects of Atonik and Profarm in these conditions. The findings highlight the potential of N3M as an effective tool for improving black pepper resilience under environmental stress, particularly in regions affected by water scarcity or excess moisture. In contrast, Atonik and Profarm also provided positive effects, though to a lesser extent. These results underscore the importance of nutrient supplementation in mitigating the negative impacts of abiotic stresses on crop growth and productivity. Further research is necessary to evaluate the long-term effects of these fertilizers across different environmental conditions, soil types, and pepper cultivars, to optimize their application in sustainable black pepper cultivation.

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