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Optimizing Expired Chili Pepper Seeds: Interaction of Natural PGRs and Soaking Duration to Enhance Viability and Vigor

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ABSTRACT

Background: In Indonesia, the existence of the expired seeds of chili pepper are sometimes circulated among the farmers. An effort is then required in order to overcome and ensure the supply of this commodity. This study was then conducted to assess the effect of giving natural plant growth regulators (PGRs), soaking duration and their interaction to the viability and vigor of expired chili pepper seeds.

Methods: This experiment included factorial completely randomized design (CRD) consisting of 2 factors with 3 replications. The first factor was the treatment of giving natural PGRs with a concentration of 25% consisting of 7 (seven) treatment levels involving mineral water and several extracts shallot, tomato, moringa leaf, corn extract, aloe vera and banana tuber, whereas the second factor was treatment of soaking time duration treatment.

Result: The results showed that both the application of various natural PGRs and the soaking duration had significant to highly significant effects on the viability and vigor of expired chili pepper seeds. However, the interaction between the application of natural PGRs and soaking duration did not significantly affect viability and vigor. This is because one factor exerted a more dominant influence than the other, preventing the two factors from working synergistically.

Key words: Expired seed, Natural PGRs, Soaking treatment, Viability, Vigor.

INTRODUCTION

In Indonesia, chili pepper is a high-value vegetable commodity with annual demand rising due to population growth and industrial needs (Pusat Data dan Sistem Informasi Pertanian, 2023). Its high price fluctuations significantly contribute to national inflation, often caused by supply shortages that fail to meet consumer demand in several (Wahyuni *et al*., 2024; Nauli, 2016).

In order secure a resilient and sustainable supply of this essential commodity, government policies must accelerate domestic production by integrating agricultural technology. Because conventional farming alone cannot meet growing demands, adopting advanced innovations such as modern seed technologies is crucial. These technologies enhance genetic potential, pest resistance and climate resilience, serving as a vital catalyst that transforms high-level policy goals into measurable agricultural output at the farm level (Rusastra *et al*., 2005).

Seed technology innovation can support the program and boost yields, especially in low-production chili pepper regions. A primary bottleneck to high productivity is the shortage and inconsistent market availability of certified seeds, which forces smallholder farmers to use low-grade or expired alternatives, compromising yields from the start (Saputra *et al*., 2022; Tetteh *et al*., 2019). Certified high-quality seeds provide essential genetic purity, physiological vigor and phytosanitary health needed for uniform field establishment. With robust metabolic machinery to withstand environmental stress, these pathogen-free seeds produce resilient seedlings with superior growth and nutrient uptake, maximizing final crop productivity (Sembayu *et al*., 2021).

In various agricultural regions across Indonesia, outdated or expired chili pepper seeds are occasionally distributed and circulated among farmers due to unforeseen delays in the planting schedule. This problematic situation is heavily driven by shifting planting seasons caused by climate unpredictability, which is further exacerbated by logistical bottlenecks and delays in the regional seed supply chain. Consequently, farmers are often forced to utilize these sub-optimal seed lots to avoid missing the remaining cultivation window. The utilization of these expired seeds directly compromises the overall quality of the establishment phase, ultimately resulting in a substantial decrease in final crop yields. Due to severe physiological deterioration, these seeds suffer from a

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drastic reduction in initial viability and vigor, which severely impairs the germination process. Consequently, even when sown in an optimum growth medium with ideal environmental conditions, the weakened embryos lack the metabolic energy required for successful emergence, leading to patchy plant stands and poor field performance (Ernawati *et al*., 2017; Gundala *et al*., 2018).

One of the efforts to improve both the viability and vigor of expired seeds is through invigoration treatment. Seed invigoration is a specific treatment given to seeds before planting in order to increase the ability to germinate and seed vigor (Ilyas, 2012). Furthermore, the invigoration technique that can be conducted is priming, in which seed hydration process is conducted through controlled soaking so that the seeds absorb water but do not germinate (Ratnaningtyas and Endang, 2019). Seed priming has several advantages, such as more uniform sprout growth, reduced weeding, more vigor, better final tolerance, faster flowering, earlier harvest and higher yields (Heraniati, 2013).

Seed priming can be done by adding certain ingredients containing plant growth regulators (PGRs). The PGRs are non-nutrient organic compounds that can stimulate or inhibit plant growth. Several research results have shown that seed priming with the addition of natural PGRs has an effect on restoring seed viability and vigor. Priming with corn extract containing natural cytokinins can increase the viability of expired melon and chili seeds (Sholeha *et al*., 2023; Mubarok *et al*., 2021; Halimursyadah *et al*., 2015). He application of shallot extract containing auxin and gibberellin can increase germination power, growth rate and root length of cocoa seed sprouts (Darojat, 2014). In addition, seed priming using banana stem extract containing natural cytokinins can also increase the growth of mung bean plants (Muvidah *et al*., 2017).

In addition to the selection of natural plant growth regulators (PGRs), the duration of soaking also affects the effectiveness of priming in increasing seed viability and vigor. The optimum duration of soaking can maximize water imbibition by seeds so that it supports germination (Lakitan, 1996; Lusiana, 2013). Soaking for too long can cause damage to seeds and inhibit germination (Khan, 1997; Ai and Ballor, 2010).

The objective of this research was to investigate the effects of various natural plant growth regulators (PGRs) and soaking durations on priming expired chili pepper seeds to enhance their viability and vigor. Six types of natural PGR sources were evaluated: Extracts of shallot, tomato, moringa leaves, corn, aloe vera and banana stems. These organic materials were selected due to their affordability, high availability and rich content of essential PGRs, such as auxins, gibberellins and cytokinins, which can help restore seed quality. Therefore, the primary objective was to determine how these natural PGR types and their corresponding soaking times interact to optimize the restoration of viability and vigor in expired chili pepper seeds.

MATERIALS AND METHODS

This study was mainly conducted through research process start from November 2022 to January 2023 in the Laboratory of Food Crop and Horticultural Seed Supervision and Certification. This research used a factorial completely randomized design (CRD) consisting of 2 factors with 3 replications. The first factor was the treatment of giving natural PGRs with a concentration of 25% consisting of 7 (seven) treatment levels, *i.e*. T0 = Mineral water; T1 = Shallot extract; T2 = Tomato extract; T3 = Moringa leaf extract; T4 = Corn extract; T5 = Aloe vera extract and T6 = Banana tuber extract. The second factor was the treatment of soaking time consisting of 4 (four) treatment levels, namely: L0 = 0 hours L1 = 12 hours L2 = 24 hours L3 = 36 hours. Mainly on the basis of these treatment factors, there are 28 combinations of experimental treatments in which each treatment was repeated 3 times so that 84 experimental units were obtained. The data obtained were analyzed using analysis of variance (ANOVA) using SPSS software. If there is a significant difference, then further testing is carried out using the honestly significant difference test (HSD) at the 5% level.

The seeds used in this research is chili pepper seeds (*Capsicum frutescens* L.) with the variety of Taruna, taken from PT. East West Seed Indonesia. The seeds used had expired for 1.5 years since May 2021 as stated on the packaging. Expired chili pepper seeds were soaked in water for 5 minutes. Seeds that physically sink are considered to have a chance of germinating, which are then used for experiments with 25 seeds used per experimental unit. The seedling tray is then placed in a shady and humid place under ambient laboratory conditions. The room temperature during the study fluctuated between 26°C to 30°C, with a relative humidity of approximately 70% to 80% following a natural tropical photoperiod.

Several types of natural PGRs in the form of extract derived from shallot, tomato, moringa leaves, corn, aloe vera and banana tuber. Each extract was prepared through a refining process using a blender with added water. The ratio of extract and water used was 1:1 (250 grams of material: 250 ml of water). The refined material was then filtered using a sieve to separate it from the dregs. The resulting solution was used as a stock solution with a concentration of 100%. The extract of each material with a concentration of 25% as much as 200 ml was made by mixing 50 ml of stock solution with 150 ml of water. The selection of a uniform 25% concentration across all seven PGR sources was implemented as a baseline screening concentration to allow a direct, standardized comparison among the distinct natural extracts.

Chili pepper seeds that have been soaked for 5 minutes are then drained. The seeds are then soaked in a natural ZPT solution with a concentration of 25% for 12, 24 and 36 hours. Seeds soaked in mineral water for 12, 24 and 36 hours are used as controls. Therefore, the seeds

that have been soaked are then sown in planting media in the form of seedling trays with a mixture of soil and manure in a ratio of 3:1. Seeds are sown in seedling trays to a depth of 1 cm. The seedling tray is then placed in a shady and humid place.

Several parameters observed include maximum germination potential (%), germination capacity (%), germination rate, growth rate (%), uniformity of germination (%), vigor index (%) and normal seedling dry weight (gram). The maximum growth potential was calculated based on the percentage of seeds that are able to become normal sprouts 14 days after planting (DAP) per number of seeds that are germinated. Germination capacity was calculated based on the percentage of the number of normal sprouts at 7 DAP and 14 DAP compared to the number of seeds that germinated, whereas germination rate was measured by counting the number of days required for the emergence of the radicle or plumule during a certain period (7 days). Furthermore, growth rate was observed every day on the increase in the percentage of normal sprouts divided by 24-hour run and the uniformity of germination was measured based on optimum normal sprouts at 7 and 14 DAP. For vigor index, it was determined according to the number of normal sprouts in the first count, at 7 DAP. The last is normal dry weight of sprouts in which carried out at the end of the observation (day 14) by separating the normal sprouts from their cotyledons, the sprouts were then put into paper bags and heated at 60°C for 3 × 24 hours.

RESULTS AND DISCUSSION

The results of variance analysis as presented at Table 1 show that the treatment of giving several natural PGRs and soaking time (L) had a significant effect on most of the observation parameters of the viability and vigor of expired chili pepper seeds. However, there is no significant interaction between natural PGRs and soaking time.

The treatment of giving various natural PGRs gave a significant to very significant effect to parameters of germination potential and rate, growth rate, uniformity of germination, vigor index and normal dry weight of seedlings. These results are in line with the previous study which showed that the application of natural PGRs, such as garlic extract, can increase seed growth and vigor by stimulating enzyme activity, hormone synthesis and increasing cell membrane permeability (Dewi *et al*., 2022). Furthermore, natural PGRs derived from plant extracts effectively supply exogenous phytohormones like gibberellins to restore the germination potential and growth speed index of deteriorated pepper (Capsicum) seeds. The enhancement of biological parameters, including the accumulation of seedling dry weight, further highlights the efficacy of organic and plant-based priming agents in driving cell elongation and early metabolic activation during the critical phases of germination (Ellya *et al*., 2026). Therefore, natural PGRs can improve seed viability and vigor by improving the germination process, root growth and chlorophyll formation (Sutopo, 2010).

The duration of soaking has a very significant effect to the all parameters observed. Optimal soaking duration can increase water imbibition, enzyme activity and mobilization of food reserves in the seeds, thereby increasing seed viability and vigor (Sutopo, 2010). Soaking for too long can cause embryo damage and decreased seed vigor due to lack of oxygen (Kartika and Sudrajat, 2016).

The interaction between the treatment of natural PGRs giving and soaking duration was not significantly affect all parameters. The absence of significant interaction is thought to be caused by one factor having a more dominant effect than the other, so that the two factors do not work synergistically (Lubis *et al*., 2018). Non significant interaction indicates that each treatment factor has an independent influence to the parameters observed (Siregar *et al*., 2015). This aligns with the findings of Devi *et al*. (2021), who noted that while pre-sowing seed treatments are crucial for enhancing seed quality, their integrated factors often exhibit independent primary effects rather than interdependent interactions across all observation parameters.

The result of variance analysis showed that the treatment of natural PGRs giving and soaking time had a significant effect on the viability and vigor of expired chili pepper seeds, but there was no significant interaction between the two factors. This information can be used as

Table 1: Recapitulation of the results of variance analysis (F Test) to the treatment of giving several natural PGRs and soaking time on the viability and vigor of expired chili seeds.

Treatment	Parameters observed						
	MGP	GC	GR	GrR	UoG	VI	NSDW
NPGRs	NS	*	**	**	**	**	**
L	**	**	**	**	**	**	**
NPGRs × L	NS	NS	NS	NS	NS	NS	NS
CV (%)	18.34	31.30	7.18	32.64	68.01	60.95	28.94

Note:- *= Significant; **= Very significant; NS= Non significant.

-NPGRs= The giving of natural PGRs; L= Soaking time; NPGRs × L= Interaction between the giving of natural PGRs and duration of soaking; CV= Coefficient of variation.

-MGP= Maximum germination potential (%); GC= Germination capacity (%); GR= Germination rate; GrR: Growth rate (%); UoG= Uniformity of germination (%); VI= Vigor index (%) and NSDW= Normal seedling dry weight (gram).

a basis for developing techniques to improve the quality of expired chili pepper seeds through the application of natural PGRs and the regulation of soaking time.

In this study, relatively high coefficients of variation (CV) were observed for uniformity of germination (68.01%) and vigor index (60.95%). This high variance is primarily attributed to the inherent biological heterogeneity and uneven physiological deterioration within the expired seed lot. During the aging process, individual seeds within the same batch deteriorate at different rates, resulting in varying degrees of cellular and membrane damage. Consequently, when primed with natural PGRs and different soaking durations, the seeds exhibited highly sporadic and polarized responses in their germination schedules and early seedling growth. While this wide physiological variation represents a typical limitation when utilizing naturally deteriorated seed stocks, the significant main effects observed still underscore the potential of these treatments to revitalize aged chili pepper seeds.

The effect of plant growth regulators (PGRs) giving

The results of variance analysis showed that the treatment of various natural PGRs significantly affect several parameters of viability and vigor observation to the expired chili pepper seeds involving germination capacity, germination rate, growth rate, uniformity of germination, vigor index and normal seedling dry weight. However, soaking seeds in mineral water (control) produced the best values for most of these parameters (Table 2).

This occurs because plants possess internal regulatory mechanisms that strictly control how they respond to the application of exogenous plant growth regulators (PGRs). When external hormones are applied, the plant often activates feedback loops to maintain its internal hormonal balance, which can sometimes limit or alter the expected effects of the treatment. Endogenous hormones synthesized by expired chili pepper seeds if they are sufficient to support the metabolic process, then the giving of natural PGRs will not have a significant effect (Lubis *et al*., 2018). Inappropriate PGRs concentration can affect the amount and speed of absorption by seeds, thus affecting germination (Sugiono *et al*., 2024).

The low viability and vigor observed in the expired chili pepper seeds used in this study were heavily attributed to seed deterioration, a process driven by cellular degradation, lipid peroxidation and the depletion of essential nutrient reserves during prolonged storage. The cellular degradation occurs through the disruption of membrane integrity and damage to vital organelles, such as mitochondria. This is further exacerbated by lipid peroxidation, where accumulated reactive oxygen species (ROS) attack the polyunsaturated fatty acids in the seed membranes, leading to cellular leakage and metabolic dysfunction. Concurrently, the depletion of essential nutrient reserves, such as carbohydrates, proteins and lipids, occurs due to continuous baseline respiration, leaving the embryo with insufficient energy and structural blocks to support successful germination and subsequent seedling establishment. Furthermore, the condition of expired seeds causes a decrease in quality, properties, or viability of the seeds, which then results in low seed vigor (Sembayu *et al*., 2021). Previous studies have similarly demonstrated that expired or aged seeds typically exhibit a marked decline in performance, characterized by delayed radicle emergence and chronically slow vegetative growth. This prolonged storage often results in highly asynchronous (un-uniform) field emergence due to varying degrees of internal cellular damage among individual seeds within the same lot. Furthermore, the loss of seed integrity frequently manifests as morphological abnormalities during germination-such as stunted root systems or distorted hypocotyls-and, in severe cases of advanced deterioration, culminates in a complete loss of germinability, where the embryo is no longer capable of initiating metabolic activity (Sutopo, 1998).

Table 2: The average of maximum germination potential, germination capacity, germination rate, growth rate, uniformity of germination, vigor index and normal seedling dry weight for expired chili pepper seeds to the treatment of natural PGRs giving.

Natural	Parameters observed						
PGRs	MGP (%)	GC (%)	GR (day)	GrR (%)	UoG (%)	VI (%)	NSDW (gram)
T0	70.83a	41.17b	8.48a	3.82b	25.33b	10.17b	0.04b
T1	63.67a	36.67ab	9.65bc	3.15ab	14.83a	5.17a	0.03ab
T2	60.00a	30.33ab	10.08c	2.48a	7.18a	3.17a	0.03ab
T3	64.17a	32.67ab	9.96bc	2.69ab	7.83a	2.38a	0.03ab
T4	57.17a	30.33ab	9.56bc	2.55a	10.00a	6.00a	0.03a
T5	60.17a	26.83a	9.19ab	2.29a	10.17a	5.17a	0.02a
T6	63.00a	31.50ab	9.60bc	2.64a	10.00a	4.33a	0.02a
$BNJ_{0.05}$	14.37	12.82	0.85	1.14	10.36	4.01	0.01

Note:- Numbers followed by the same letter in the same column are not significantly different at honestly significant difference (HSD) 0.05 test.

T0= Mineral water; T1= Shallot extract; T2= Tomato extract; T3= Moringa leaf extract; T4= Corn extract; T5= Aloe vera extract; T6= Banana tuber extract.

Efforts to restore and enhance the physiological viability and seedling vigor of deteriorated or expired chili pepper seeds can be effectively achieved through seed invigoration techniques. These methods, which include specialized priming treatments such as osmoconditioning and hydropriming, work by initiating pre-germinative metabolic activities and repairing cellular damage within the aged embryo without triggering actual radicle emergence (Ananthi *et al*., 2014; Amin *et al*., 2021). Although the application of natural plant growth regulators (PGRs) did not yield a statistically significant effect in this study, the control treatment, which involved soaking the seeds in mineral water, it demonstrated a notable capacity to stimulate germination. This phenomenon occurs because the lower viscosity and balanced osmotic potential of mineral water facilitate a more rapid and efficient imbibition process. Consequently, this accelerated water uptake allows the seed coat to soften quickly, swiftly rehydrating the internal tissues and triggering the essential enzymatic pathways required to break embryo dormancy and initiate radicle emergence (Sutopo, 2010).

Interestingly, the post-hoc HSD test showed that the control treatment (T0, mineral water) yielded significantly higher values for GC, GrR, UoG, VI and NSDW than the natural PGR treatments (T1-T6). This indicates that the crude natural PGRs suppressed rather than enhanced the recovery of the expired seeds. Because expired seeds have weakened cell membranes and degraded embryo structures, the high solute concentration of these crude extracts likely induced osmotic stress that hindered water imbibition. Furthermore, secondary metabolites in the extracts may have exerted a phytotoxic effect on the fragile embryos. In contrast, hydro-priming with pure water (T0) minimized osmotic and chemical stress, allowing the remaining viable seeds to successfully reactivate their metabolism.

The effect of soaking time of plant growth regulators (PGRs)

The results of the treatment for soaking time duration was provide at Table 3. The analysis of variance (ANOVA) revealed that the soaking duration exerted a highly significant influence on all evaluated seed quality parameters. Specifically, variations in soaking time substantially affected critical viability and germinability metrics, including maximum germination potential, total germination capacity and germination uniformity. Furthermore, this treatment significantly altered seed vigor indicators, such as the germination rate, vegetative growth speed, overall vigor index and the final dry weight of normal seedlings.

Seed soaking for 12 hours result in the best values for most of the observation parameters, which are not significantly different from soaking treatments for 0 and 24-hour, but significantly different for 36 hours. Seed soaking for 12 hours able to maximize the water imbibition process by the seeds, making it easier for the seeds to enter the lag phase where enzyme reactions and food reserve breakdown occur (Lakitan, 1996). This process provides energy used for radicle cell elongation and radicle emergence. The duration of absorption of plant growth regulators (PGRs) and nutrients is related to the soaking time. Seeds that are soaked for the proper time will germinate well (Lusiana, 2013).

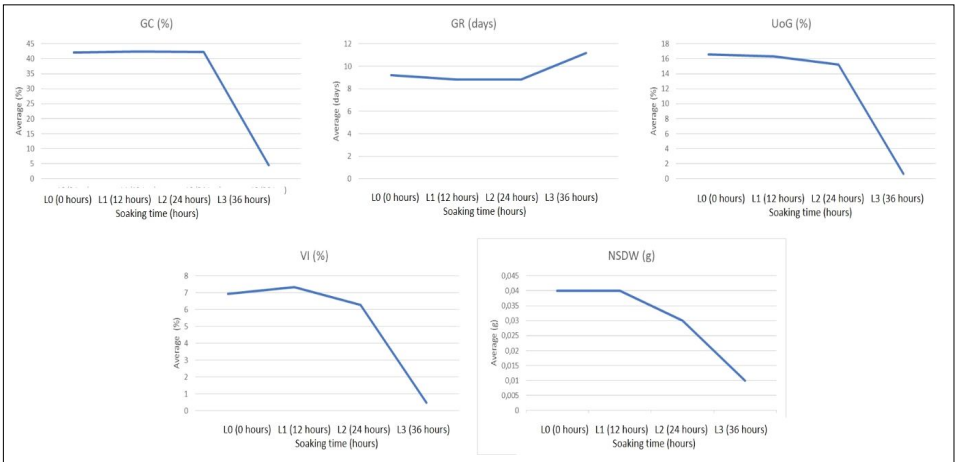
The experimental results demonstrated that extending the soaking duration to 36 hours resulted in the lowest scores for both seed viability and vigor indicators. This physiological decline is strongly attributed to the hypoxic or anoxic conditions induced by prolonged submersion, which deprives the seed embryo of oxygen required for aerobic respiration. Under these oxygen-deficient conditions, the seeds are forced to shift their metabolic pathways toward anaerobic fermentation, leading to the phytotoxic accumulation of ethanol and acetaldehyde. Furthermore, excessive water imbibition over this extended period causes severe imbibitional injury, disrupting cell membrane integrity and triggering the leakage of essential intracellular solutes, which ultimately suppresses seed metabolism and halts germination (Halimursyadah, 2015; Yoneyama and Natsume, 2010). An excessively prolonged soaking duration can induce severe anoxia, a state of critical oxygen deprivation within the seed matrix. This lack of oxygen severely suppresses the normal aerobic respiration process required for energy production, forcing the embryo to shift toward inefficient

Table 3: The average of maximum germination potential, germination capacity, germination rate, growth rate, uniformity of germination, vigor index and normal seedling dry weight for expired chili pepper seeds to the treatment of soaking time duration.

Soaking time	Parameter observed						
	MGP (%)	GC (%)	GR (day)	GrR (%)	UoG (%)	VI (%)	NSDW (gram)
L0	75.90b	42.00b	9.20a	3.60b	16.57b	6.95b	0.04b
L1	76.57b	42.38b	8.81a	3.63b	16.29b	7.33b	0.04b
L2	76.29b	42.29b	8.82a	3.61b	15.24b	6.29b	0.03b
L3	22.10a	4.48a	11.19b	0.37a	0.67a	0.48a	0.01a
$BNJ_{0.05}$	9.40	8.39	0.56	0.75	6.78	2.62	0.01

Note:- Numbers followed by the same letter in the same column are not significantly different at honestly significant difference (HSD) 0.05 test.

L0= 0 hour; L1= 12 hours; L2= 24 hours and L3= 36 hours.



(GC): Germination Capacity; (GR): Germination rate; (UoG): Uniformity of germination; (VI): Vigor index and (NSDW): Normal seedling dry weight.

Fig 1: Effect of soaking time duration of L0 (0 hour), L1 (12 hours), L2 (24 hours) and L3 (36 hours) on the germination and vigor parameters of expired chili pepper seeds.

anaerobic pathways. Consequently, this metabolic disruption systematically impairs enzyme reactivation and cellular repair, thereby impeding successful radicle emergence and halting the entire germination process (Ai and Ballor, 2010). Other studies have similarly explained that exceeding the optimal priming threshold through over-soaking invariably leads to a substantial reduction in seed germinability. When seeds that are physiologically primed and ready to germinate are left continuously submerged, the artificial environment restricts gas exchange during a highly critical growth window. This prolonged exposure not only causes severe imbibitional injury but also suppresses the enzymatic activities required to break down seed storage reserves, thereby preventing successful seedling establishment (Khan, 1997).

Overall, the treatment of soaking time affects both the viability and vigor of expired chili pepper seeds (Fig 1). Soaking for 12 hours produces the best values for most of observation parameters. This phenomenon occurs because the treatment optimizes the water imbibition process within the seed matrix, allowing for a controlled rate of hydration. By regulating moisture uptake, the seeds can reach the critical threshold required to trigger metabolic reactivation while simultaneously avoiding the hypoxic or anoxic conditions that typically cause cell damage due to limited oxygen availability. On the other hand, an excessively prolonged soaking duration, such as 36 hours, exerts a detrimental effect on the physiological quality of expired chili pepper seeds, leading to a significant reduction in both viability and vigor. Extended submersion deprives the seed embryo of necessary oxygen, shifts cellular respiration from an aerobic to an anaerobic pathway and triggers toxic ethanol accumulation. Furthermore, this prolonged state induces severe membrane disruption, causing critical cellular solutes and nutrients to leak out, which ultimately accelerates seed mortality rather than promoting germination.

CONCLUSION

The analysis of variance (ANOVA) revealed that while both the application of natural plant growth regulators (PGRs) and soaking duration independently exerted highly significant effects on the viability and vigor of deteriorated chili pepper seeds, their interaction was statistically insignificant. Interestingly, the control treatment using plain mineral water yielded the most superior results, indicating that a single dominant factor drove the seed's physiological recovery rather than a synergistic effect. Consequently, for farmers and seed technologists, it is practically recommended to prioritize simple hydropriming (soaking in clean mineral water) over natural PGRs as a highly cost-effective and efficient method to restore low-vigor seeds, while strictly adhering to the optimized soaking duration [insert optimal duration, *e.g.*, of 12 hours] to maximize seed performance.

Conflict of interest

The authors declare that there are no conflicts of interest associated with this manuscript. The authors have no financial, personal, or professional relationships that could have influenced the research, analysis, or interpretation of the results reported in this manuscript.

REFERENCES

Ai, N.S. and Ballor, M. (2010). Peranan air dalam perkecambahan biji. *Journal Ilmiah Sains*. **10:** 2. https://repo.unsrat.ac.id/508/1/SAINS_10%282%29_ OKTOBER_2010.pdf.

Amin, M.A.S., Lubis, A.T. and Lubis, L. (2021). Osmoconditioning treatment to improve the viability and vigor of chili (*Capsicum annuum* L.) seeds. *IOP Conference Series: Earth and Environmental Science*. **648(1):** 012178.

Ananthi, M., Selvaraju, P. and Sundaralingam, K. (2014). Effect of bio-priming using bio-control agents on seed germination and seedling vigour in chilli (*Capsicum annuum* L.) 'PKM 1'. *Journal of Horticultural Science and Biotechnology*. **89(5):** 564-568. https://doi.org/10.1080/14620316.2014.11513121.

Darojat, M.K. (2014). Pengaruh Konsentrasi dan Lama Perendaman Ekstrak Bawang Merah (*Allium cepa* L.) Terhadap Viabilitas Benih Kakao (*Theobroma cacao* L.). Skripsi. Universitas Islam Negeri Maulana Malik Ibrahim Malang.

Dewi, A.K., Suyono. and Nugroho, L.H. (2022). The effect of garlic extract on seed germination and seedling growth of chili pepper. *Journal Ilmu Pertanian.* **15(2):** 125-133.

Devi, K., Barua K.P. and Barua, M. (2021). Integrated effect of pre-sowing seed treatment, sowing windows and seasons on seed yield and quality of greengram. *Legume Research.* **44(8):** 956-961. doi: 10.18805/LR-4174.

Ellya, H., Wahdah, R., Ainawati, S., Apriani, R.R. and Gazali, A. (2026). Seeds viability of hiyung (Local cultivar) cayenne pepper (*Capsicum frutescens* L.) applied by water hyacinth root extract. *Agricultural Science Digest*. doi: 10.18805/ag.DF-749.

Ernawati, P.R. and Bejo, S. (2017). Respon benih cabai merah (*Capsicum annuum* L.) kadaluarsa pada lama perendaman air kelapa muda terhadap viabilitas, vigor dan pertumbuhan bibit. *Journal Agritrop*. **15(1):** 71-83. https://doi.org/10.32528/agr.v15i1.794.

Gundala, B.T., Trisda, K. and Halimursyadah. (2018). Pengaruh konsentrasi auksin dalam hydropriming benih cabai yang berbeda tingkat kadaluarsa terhadap viabilitas benih. *Journal Ilmiah Mahasiswa Pertanian: Universitas Syiah Kuala.* **3(4):** 159-166. https://doi.org/10.17969/jimfp.v3i4.9378.

Halimursyadah, H. (2015). Pengaruh pemberian zat pengatur tumbuh alami terhadap pertumbuhan dan produksi tanaman bawang merah (*Allium ascalonicum* L.). *Journal Floratek*. **10(1):** 26-34.

Heraniati. (2013). Peningkatan Daya Adaptasi Cekaman Salinitas Benih Beberapa Varietas Padi dengan Teknologi Seed Priming. Skripsi. Universitas Hasanuddin. Makassar.

Ilyas, S. (2012). Ilmu dan Teknologi Benih: Teori dan Hasil-Hasil Penelitian. IPB Press. Bogor. 138 pages.

Kartika, E. and Sudrajat, D.J. (2016). Pengaruh lama perendaman dan konsentrasi giberelin terhadap viabilitas benih jarak pagar (*Jatropha curcas* L.). *Journal Ilmu Kehutanan*. **10(1):** 45-54.

Khan, A.A. (1997). Preplant Physiological Seed Conditioning. CRC Press. *Horticultural Reviews.* **13:** 131-181.

Lakitan, B. (1996). Dasar-Dasar Fisiologi Tumbuhan. PT Raja Grafindo Persada.

Lubis, L., Idwar. and Purba, R.J. (2018). Pengaruh pemberian ekstrak bawang putih (*Allium sativum* L.) dan lama perendaman terhadap viabilitas benih cabai rawit (*Capsicum frutescens* L.). *Journal Agroteknologi.* **8(2):** 51-60.

Lusiana, N. (2013). Pertumbuhan dan produksi tanaman tomat (*Lycopersicum esculentum* Mill.) pada berbagai konsentrasi pupuk organik cair dari limbah tahu. Skripsi. Universitas Negeri Yogyakarta.

Mubarok, A., Jenal, M. and Resti, F. (2021). Pengaruh konsentrasi giberelin (GA3) dan lama perendaman dalam meningatkan perkecambahan benih padi (*Oryza sativa* L.) varietas ciherang (Kadaluarsa). *Journal Agroteknologi dan Sains (JAGROS).* **5(2):** 363-376.

Muvidah, S., Kiswardianta, R.B. and Ardhi, M.W. (2017). Pengaruh Konsentrasi Perendaman Ekstrak Bonggol Pisang dan Air Kelapa terhadap Pertumbuhan Kacang Hijau (*Phaseolus radiatus*). Prosiding Seminar Nasional Simbiosis II. Universitas PGRI Madiun. Madiun.

Nauli, D. (2016). Fluctuation and price disparity of chili in Indonesia. *Journal Agrosains dan Teknologi.* **1(1):** 57-69. https://doi.org/10.24853/jat.1.1.57-70.

Pusat Data dan Sistem Informasi Pertanian. (2023). Outlook Komoditas Pertanian Subsektor Hortikultura Cabai. Sekretariat Jenderal Kementerian Pertanian. (77 pages).

Ratnaningtyas, F.R and Endang, P. (2019). Pengaruh perlakuan organomatrixpriming terhadap peningkatan mutu fisiologis benih cabai (*Capsicum annuum* L.). *Buletin Anatomi dan Fisiologi.* **4(1):** 45-54. https://doi.org/10.14710/baf.4.1.2019.45-54.

Rusastra, I.W., Sumaryanto. and Simatupang, P. (2005). Agricultural development policy strategies for Indonesia: Enhancing the contribution of agriculture to poverty reduction and food security. *Forum Penelitian Agro Ekonomi.* **23(2):** 84-101. doi: 10.21082/fae.v23n2.2005.84-101.

Saputra, J., Amir, R.A., Mumin, N. and Sutariati, G.A.K. (2022). Persistence and breaking of local chilli seed dormancy using seed bio-invigoration techniques. *Journal Agrotek Tropika.* **8(2):** 391-400. https://www.researchgate.net/publication/356334957_PERSISTENSI_DAN_PEMATAHAN_DORMANSI_BENIH_CABAI_RAWIT_LOKAL_MENGGUNAKAN_TEKNIK_BIO-INVIGORASI_BENIH.

Sembayu, R.S., Sugiyanta, S. and Hartati, S. (2021). Pengaruh invigorasi terhadap viabilitas dan vigor benih kacang tanah (*Arachis hypogaea* L.) yang mengalami penuaan dipercepat. *Journal Agronomi Indonesia.* **49(1):** 71-79.

Sholeha, N., Hidayat, R. and Dewanti, F.D. (2023). Effect of cutting sources and concentration of rootone-F plant growth regulator on growth of long pepper (*Piper retrofractum* Vahl.) cuttings. *Agro Bali: Agricultural Journal.* **6(3):** 750-760. https://doi.org/10.37637/ab.v6i3.1319.

Siregar, A.P., Zuhry, E., dan Sampoerno. (2015). Pertumbuhan bibit gaharu (*Aquilaria malaccencis*) dengan pemberian zat pengatur tumbuh asal bawang merah. *Jom Faperta.* **2:** 1. https://media.neliti.com/media/publications/184543-ID-pertumbuhan-bibit-gaharu-aquilaria-malac.pdf.

Sugiono, T.S., Prahardini, P.E.R., Antarlina, S.S., Fidiyawati, E., Ashari, H., Kilmanun, J.C. and Latifah, E. (2024). 13th international conference of green technology (ICGT 2023). *IOP Conf. Series: Earth and Environmental Science.* **1312(2024):** 012004. doi: 10.1088/1755-1315/1312/1/012004.

Sutopo, L. (2010). Teknologi Benih (Edisi Revisi). PT Raja Grafindo Persada.

Sutopo, L. (1998). Teknologi Benih. Raja Grafindo Persada.

Tetteh, R., Aboagye, M.L., Darko, R. and Osafo, A.E. (2019). Physiological seed quality in relation to maturity stage in two pepper (*Capsicum annuum* L.) cultivars. *Indian Journal of Agricultural Research.* **53(5):** 604-608. doi: 10.18805/IJARe.A-419.

Wahyuni, T.S., Satriani, R. and Mandamdari, A.N. (2024). Pengaruh fluktuasi harga cabai rawit merah terhadap inflasi di kabupaten banyumas. *Mimbar Agribisnis: Journal Pemikiran Masyarakat Ilmiah Berwawasan Agribisnis*. **10(2):** 1866-1877. doi: http://dx.doi.org/10.25157/ma.v10i2.13684.

Yoneyama, K. and Natsume, M. (2010). Allelochemicals for plant-plant and plant-microbe interactions. *Comprehensive Natural Products II.* **4:** 539-561. https://doi.org/10.1016/B978-008045382-8.00105-2.