

Article

Influence of Seed Treatments with Elicitors on the Emergence and Early Vigor of Hulled and Dehulled Vialone Nano Rice

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Abstract

Rice (*Oryza sativa*) cultivation is highly relevant for global food security, yet germination may be conditioned by the presence of the rice hull. Using hulled or dehulled rice seeds can affect germination because the hull acts as both a physical barrier and a source of inhibitory compounds. While dehulling may speed germination by improving water and gas exchange and removing allelochemicals, it also increases vulnerability to damage and pathogens. Specific seed treatments can help mitigate these challenges. This study investigated the effects of mechanical dehulling and seed soaking with different elicitors, including hydrogen peroxide (H₂O₂), *Hammada scoparia* extracts, and ferrous sulfate, on Vialone Nano rice seed emergence and early vigor. Key findings revealed that dehulled seeds presented better emergence compared to hulled seeds, likely due to the removal of physical barriers and improved water uptake. However, hulled seeds were more responsive to the treatments, showing marked improvements in emergence speed and seedling vigor. The results demonstrate that while dehulling provides a natural advantage, seed treatments with elicitors effectively bridges the performance gap for hulled seeds. These strategies may offer sustainable approaches to improve crop establishment and overall productivity in the local rice farming systems.

Keywords: elicitors; germination; *Oryza sativa*; seed hull; seed soaking; sustainability

1. Introduction

In recent years, growing pressure has been placed on the agri-food sector to ensure global food security [1]. A primary driver is the degradation of arable land dedicated to food production, triggered by rising soil erosion, aridity, salinization, and declining organic carbon content [2]. This challenge is further aggravated by the climate change crisis and increasing costs of farmers inputs, such as irrigation, fertilizer, and manual labor. These factors need to be addressed to cope with challenges in food production particularly with high value crops such as rice.

Rice (*Oryza sativa*) is a valued agricultural product since it is the third most cultivated crop worldwide by both total tonnage and harvested surface area [3]. Consequently, it serves as a staple food for over half of the global population [4]. Economically, its production serves as the primary source of income and livelihood across producing countries. In Europe, two-thirds of the rice production comes from Italy, where 41% is grown in the Lombardy region [5,6]. The Vialone Nano variety is much preferred for consumption by Italians, but it is characterized by high sensitivity to blast infection [7] and salinity stress



Academic Editor: Gang Wei

Received: 20 May 2026

Revised: 17 June 2026

Accepted: 25 June 2026

Published: 27 June 2026

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conditions [8]. Moreover, it has also been known to have a low yield potential. Given its cultural preference, considerable efforts have been made towards improving its yield.

High yield is a key indicator of a successful harvest. Numerous works have been directed towards understanding and improving the reproductive stage as it is directly link to yield [9,10]. However, germination should also be considered, since it dictates the trajectory of all subsequent vegetative and reproductive phases. Superior germination rates enhance seedling vigor, facilitating better field establishment and maximizing yield potential [11].

Germination is initiated by water imbibition and progresses into a triphasic process [12,13]. The first phase is described as a rapid water uptake, followed by the second or lag phase that spans from 20 to 48 h of imbibition in rice [12]. The lag phase is where key physiological processes are initiated in preparation for the third phase. This is characterized by an additional increase in water uptake, resulting in high turgor pressure within the embryo and endosperm. This escalating turgor pressure operates in tandem with the enzymatic weakening of the seed coat, inducing a mechanical rupture that permits radicle emergence [14]. To manage these complex biochemical transitions, pre-sowing strategies such as seed priming can be used to optimize germination kinetics and synchronize seedling emergence, ultimately safeguarding final crop yield.

Seed priming can boost germination through controlled water uptake, which potentiates the transcription and metabolic activities in the seed prior to radicle emergence [15]. Priming involves partial hydration followed by drying back to a moisture content suitable for standard storage. Primed seeds exhibit faster stand establishment, improved competitiveness against weeds, and often more tolerance to abiotic stresses, e.g., salinity, drought, and low temperature [16–19]. Other user-friendly practices, specifically for farmers, include seed soaking approaches. While both techniques involve hydrating seeds to boost metabolic activity, seed priming and soaking differ in their level of hydration control and physiological outcomes. Unlike priming, seed soaking involves complete immersion in an aqueous medium for a designated duration without a subsequent re-drying phase; while this accelerates initial imbibition, the hydration step is less controlled, and the seeds cannot be stored, so they need to be immediately sown [20,21].

In rice, the application of seed priming and soaking serves as a strategic intervention to overcome some cultivation hurdles, like poor seedling establishment, asynchronous emergence, and environmental stresses [22–24]. Additionally, the presence or removal of the seed hull can influence the efficiency of these treatments and subsequent germination. While hulled seeds are standard for field sowing to protect the embryo, the dehulled ones are often used in laboratory settings to study physiological mechanisms or to bypass dormancy. The hull serves as a protective layer but also acts as a primary regulator of the lag phase, as it exerts a physical pressure that the emerging radicle must overcome via increased internal turgor pressure and enzymatic softening [25]. The hull can also contain germination inhibitors (such as abscisic acid or phenolic compounds) and restricts oxygen diffusion to the embryo, which can maintain dormancy in certain genotypes [26]. Most field-scale approaches (e.g., hydropriming and water soaking) are performed on hulled seeds, as the presence of this layer helps to regulate the rate of water uptake, preventing damage that can occur if the embryo is hydrated too rapidly. Removing the hull (dehulling), although a more damaging approach for the seed, may be useful to eliminate the physical and chemical barriers to germination, leading to distinct physiological changes. Without the hull, water reaches rapidly the embryo, thus shortening the first phase of germination [12]. Dehulling is also a common technique to achieve high germination percentages in dormant varieties, as it removes the source of many hull-borne inhibitors [26].

Building on these premises, the present work aimed to investigate and potentially improve the germination performance of Vialone Nano rice. Specifically, the work focused on two complementary strategies: (1) the use of hulled and dehulled rice as sowing material and (2) the development of variety-specific seed treatments. Because the Vialone Nano variety is highly susceptible to seed-borne pathogens such as *Magnaporthe oryzae* (rice blast) or the nematode *Aphelenchoides besseyi*, dehulling could serve as a mechanical phytosanitary measure. The seed treatments to be tested in this work are based on previous findings showing that 16 h pre-soaking in water or in ferrous sulphate solution improved rice germination and tolerance to drought [18,27]. Here, additional agents, specifically hydrogen peroxide (H_2O_2) and *Hammada scoparia* plant extract, were compared with conventional water soaking and untreated seeds under controlled soil-based germination conditions. The selection of H_2O_2 and *H. scoparia* extract is based on their synergistic antioxidant and antimicrobial properties. H_2O_2 serves a dual purpose, acting as a signaling molecule to promote germination and as a disinfectant for the seed surface [28]. The phytochemical profile of *H. scoparia*, rich in phenolic and alkaloid compounds [29], provides a bio-based antimicrobial barrier and enhances the radical scavenging capacity, thereby protecting it from both oxidative damage and seed-borne pathogens.

2. Materials and Methods

2.1. Plant Materials

The experimental material consisted of *Oryza sativa* subsp. *japonica*, Vialone Nano variety. Two categories of materials were tested, namely hulled (caryopses with lemma and palea) and dehulled (with the outer hull mechanically removed) seeds. All seeds belong to the same batch produced by Innova-Tech (Piedmont, Italy) during the 2023 growing season. Seed were maintained in a storage room at controlled conditions (18 °C, dark, with low relative humidity) until use (a few months). The moisture content of both hulled and dehulled rice was 12%.

2.2. Experimental System and Treatments

The seed treatments were conducted following the protocol developed by Dueñas et al. [27]. Briefly, 75 seeds/treatments (25 seeds/replicate) were soaked for 12 h in Petri plates containing 5 mL of the following solutions (Figure 1):

- Water (W);
- Ferrous sulphate heptahydrate at 10 mM ($FeSO_4 \cdot 7H_2O$);
- Hydrogen peroxide at 75 mM and 100 mM concentrations (H_2O_2 -75, H_2O_2 -100);
- *Hammada scoparia* extract diluted to 1:2500 and 1:500 (Hs-1:2500 and Hs-1:500).

A set of non-treated (NT) hulled and dehulled seeds served as the control.

Subsequently, treated/untreated seeds were sown in well-watered soil trays (14.2 cm length × width 20.2 cm) [18]. A total of 42 trays (3 replicates × 7 treatments × 2 seed types) were prepared, each containing 80 g of unsterilized Semina BRM substrate (Vigorplant, Fombio, Lodi, Italy). For each tray, 25 seeds were sown in a 5-column × 5-row arrangement. A volume of 150 mL of tap water was uniformly supplied during sowing (0 DAS, days after sowing) whereas 100 mL of water was supplied from the 1st (1 DAS) until the 14th day (14 DAS) to sustain well-watered soil conditions. The trays were placed in a greenhouse facility (GreenTechHouse, Department of Biology and Biotechnology, University of Pavia) under the following conditions: 16/8 h light/dark, 22.4–30.3 °C, and 38–62% relative humidity. The experimental system was monitored daily for 14 days (Figure 1).

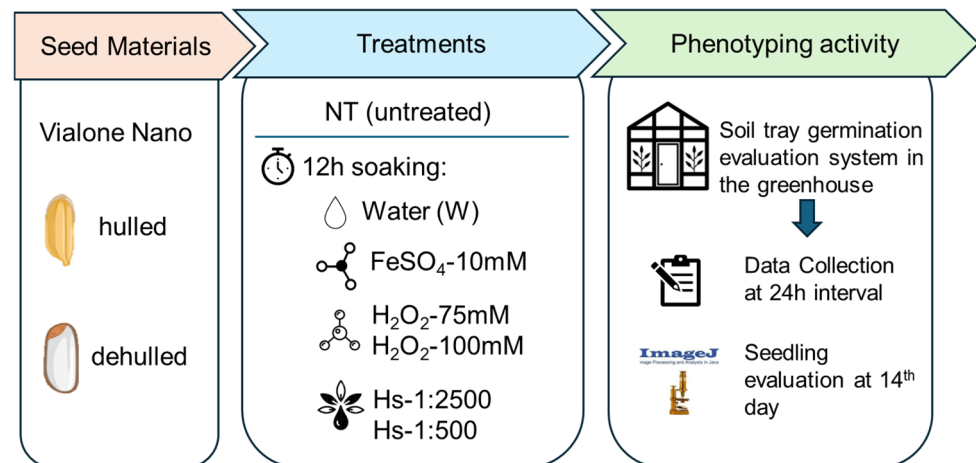


Figure 1. Overview of the experimental setup. NT, no treatment; W, water soaking; FeSO₄-10, 10 mM of ferrous sulphate heptahydrate; H₂O₂-75, 75 mM hydrogen peroxide; H₂O₂-100, 100 mM hydrogen peroxide; Hs2500, 1:2500 dilution of *Hammada scoparia* extract; Hs500, 1:500 dilution of *Hammada scoparia*.

2.3. Preparation and Characterization of the *Hammada scoparia* Extract

Hammada scoparia plant material was collected in Tunisia with the support of the Institut des Régions Arides (IRA), Medenine, Tunisia. The plant material was authenticated by botanist Dr. Mohammed Neffati according to the “Flora of Tunisia” catalogue, and voucher specimens were deposited at the herbarium of the IRA. After collection, the plant material was sun-dried and ground to a fine powder. For extract preparation, 250 g of dried powdered plant material were macerated in 1 L of 50% methanol (*v/v*) for 24 h at room temperature. After extraction, the liquid phase was recovered and filtered through a 0.45 µm membrane filter. The filtered extract was then concentrated five-fold under reduced pressure using a rotary evaporator (Rotavapor System R-300, Büchi Labortechnik AG, Flawil, Switzerland) in order to remove methanol. The resulting concentrated aqueous extract (pH 6.8) was finally filtered through a 0.22 µm membrane filter.

The prepared extract presented a total polyphenol content (TPC) of 70 ± 1.8 mg/g dry weight (DW). This was determined using the Folin–Ciocalteu colorimetric method [30], with minor modifications. Aliquots of the filtered extract were reacted with reagent, and the absorbance was measured at 725 nm using a UV–Vis spectrophotometer. Gallic acid was used to generate the calibration curve, and the total polyphenol content was expressed as gallic acid equivalents (GAE).

2.4. Phenotyping Parameters

Seedling emergence data were collected at a 24 h interval. The emergence percentage (E%), index (EI), speed (MET), peak values (PV), root to shoot ratio (R:S), and seedling vigor index (SVI) were calculated, as indicated below.

The emergence percentage (E%) was calculated as the accumulative number of emerged seedlings (defined as ≥ 1 mm above the soil surface) recorded on each day and expressed as a percentage using the formula:

$$E\% = \left(\frac{\text{number of emerged seedlings}}{\text{total number of seeds sown}} \right) \times 100$$

The mean emergence time (MET) was measured to indicate average speed of seedling emergence, expressed as days, and was determined based on:

$$MET (days) = \frac{\sum[(N1 \times 1) + \dots + (N14 \times 14)]}{\sum(N1 + \dots + N14)} \quad (1)$$

where N = the count of emerged seedlings at the day of recording.

The peak value (PV) was used to assess emergence vigor by integrating the speed and magnitude of cumulative seedling emergence across the duration of assessment. It was calculated according to the following equation:

$$PV (a.u.) = \frac{Nn}{Dn} \quad (2)$$

where N = the number of germinated seeds on each day; D = the specific day when the germinated seeds were counted; and a.u. = arbitrary units.

The emergence index (EI) is indicative of a weighted cumulative index. The index was determined by summing the ratio of the number of newly emerged seedlings recorded at each observation time to the corresponding day after sowing:

$$EI (a.u.) = \sum[(14 \times N1) + (13 \times N2) + \dots + (1 \times N14)] \quad (3)$$

where N = the number of germinated seeds on each day, and a.u. = arbitrary units.

At 14 days after sowing (DAS), five seedlings were randomly selected from each of the three replicates for measuring seedling growth. Each tray was submerged in water to loosen the soil attached to the roots and was carefully cleaned to avoid damage. Roots and shoots were placed on a black cloth, and images were taken using a photo camera (Apple iPhone 8Plus, California, CA, USA). The images were imported in the free online software ImageJ version 1.54g (<https://imagej.nih.gov/ij/download.html>) for subsequent processing and length measurements provided in millimeters (mm).

The root to shoot ratio (R:S) was determined by dividing the average root length by the corresponding average shoot length. Values were expressed in arbitrary units (a.u.). the seedling vigor index (SVI) was determined according to the following equation:

$$SVI (a.u.) = (shoot\ length + root\ length) \times E\% \text{ at } 14DAS \quad (4)$$

2.5. Statistical Analysis and Data Visualization

One-way and two-way ANOVAs with *post hoc* Duncan's statistical test were conducted using an online software (<https://houssein-assaad.shinyapps.io/TableReport/>, [31]). Given the inherent structural differences between seed groups, one-way ANOVA was used test to evaluate the effects of seed priming treatments within each seed group (hulled and dehulled). The two-way ANOVA was subsequently used to assess the interaction effect between seed type and treatment. Data normality and homoscedasticity were evaluated prior to analysis using the Shapiro–Wilk and Levene tests in OriginPro 2026 Learning Edition software (OriginLab Corporation, Northampton, MA, USA). Statistical significance for all main effects and interactions was predetermined at a threshold of $p < 0.05$, and subsequent mean comparisons were resolved using Duncan's *post hoc* test.

Data visualization was conducted using OriginPro 2026, while heatmaps were generated using MetaboAnalyst 6.0 (<https://www.metaboanalyst.ca/docs/Publications.xhtml>).

3. Results

3.1. Hulled and Dehulled Rice Showed Different Seedling Emergence After Seed Treatments

To evaluate the seedling emergence of hulled and dehulled seeds following treatments with elicitors, E%, MET, and PV parameters were calculated (Figure 2, Tables S1 and S2). Among the non-treated controls (NT), the maximum emergence (E%) of hulled rice was significantly lower ($46.67 \pm 4.81\%$, Figure 2a) than that of the dehulled ones ($74.67 \pm 4.81\%$, Figure 2b), as supported by the statistical analyses in Table S3 (see reported *p*-value for seed type 0.001). Furthermore, the onset of emergence in hulled seeds occurred at 3 days after sowing (DAS), whereas dehulling advanced the initiation of emergence to 2 DAS.

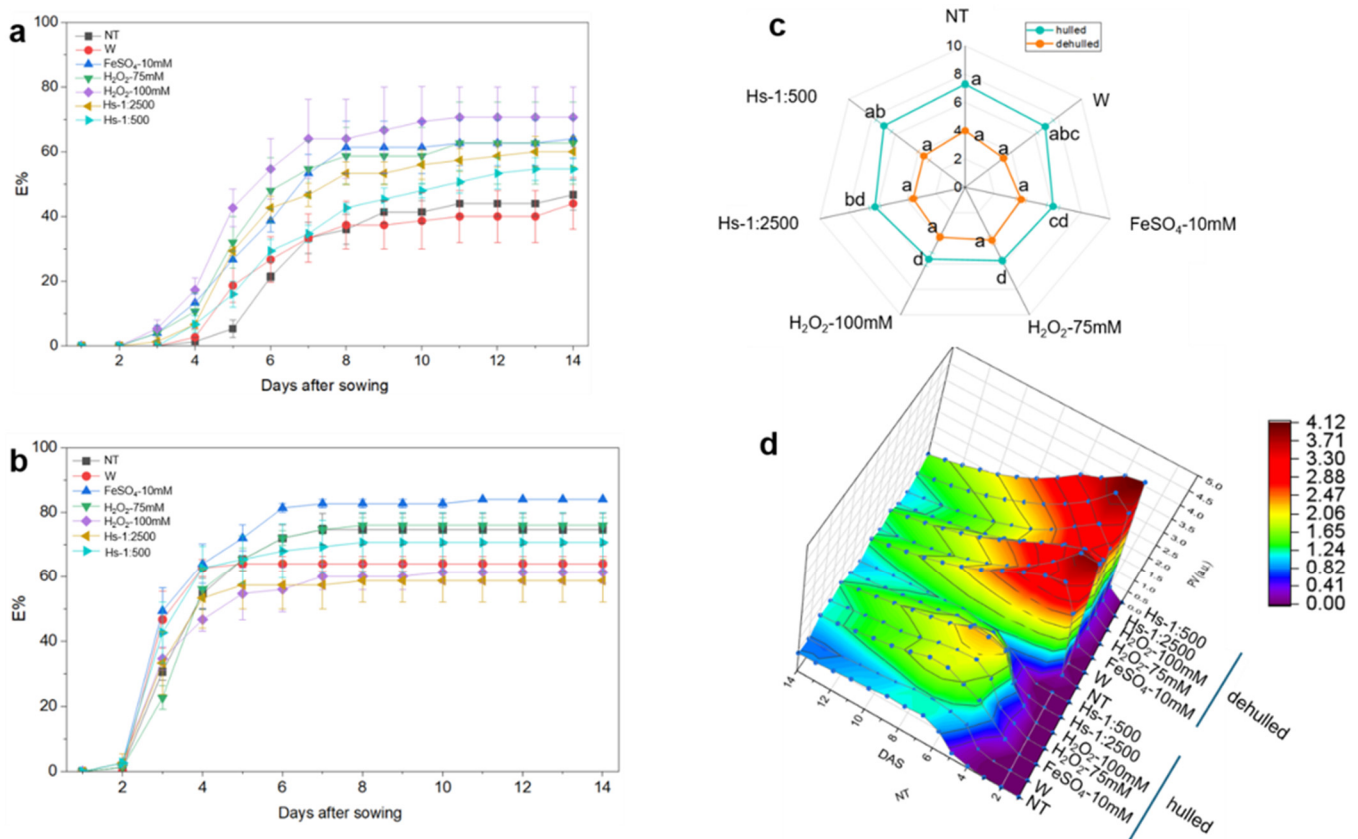


Figure 2. Evaluation of seedling emergence from hulled/dehulled rice seeds subjected to soaking treatments with different elicitors. (a) Emergence percentage (E%) in hulled seeds. (b) Emergence (E%) in dehulled seeds. (c) Mean emergence time (MET) values. (d) Peak value (PV). Statistical differences ($p < 0.05$) were determined by one-way ANOVA with *post hoc* DUNCAN test, conducted separately for hulled and dehulled seeds. Different letters indicate statistically significant differences among samples. For E% and PV, all values and statistics are provided in Tables S1 and S2. NT, non-treated control; W, water soaking; FeSO₄-10 mM, treatment with 10 mM ferrous sulphate heptahydrate solution; H₂O₂-75 mM, treatment with 75 mM hydrogen peroxide solution; H₂O₂-100 mM, treatment with 100 mM hydrogen peroxide solution; Hs-1:2500, treatment with 1:2500 dilution solution of *Hammada scoparia* extract; Hs-1:500, treatment with 1:500 dilution solution of *Hammada scoparia* extract; a.u., arbitrary units.

Even if the applied treatment did not significantly improve E% at the end of the monitoring period, emergence speed was accelerated as evidence by MET values. Untreated hulled seeds required 7 days to emerge, while untreated dehulled rice only took an average of 4 days (Figure 2c). In relation with the applied seed soaking, FeSO₄-10 mM, Hs-1:2500, and both H₂O₂ treatments were able to induce a faster emergence (≤ 6 days) in the hulled seeds compared to their respective NT. However, this was not evidenced in the dehulled

seeds. These data were further supported by the daily calculated peak value (PV). In hulled seeds, PV was reached at 6 DAS, with the highest value recorded from seeds treated with 100 mM H₂O₂ (2.28 ± 0.39), whereas dehulled rice peaked at 4 DAS without any significant difference among the treatments (Figure 2d, Table S2).

When considering the two-way ANOVA, taking into consideration both treatments and seed type, significant *p*-values were registered mainly for the seed type (Table S3). Therefore, removing the hull substantially impacted seedling emergence.

3.2. Seed Treatments Enhance Seedling Growth in Hulled Rice

The effect of the seed soaking with elicitors was also assessed at the seedling growth level (Figure 3). To do so, the shoot and root length as well as the root to shoot ratio (R:S) were calculated. All the treatments applied on hulled rice, except W, induced longer shoot growth compared to NT (Figure 3a). This was most evident for the FeSO₄-10 mM treatment, which resulted in a significant increase in the root growth as well (Figure 3c). Seedling growth from dehulled seeds showed no significant differences between the treated and untreated groups (Figure 3b,d). The two-way ANOVA indicated that only shoot length varied significantly based on seed type, treatment, and their interaction (Table S3). Seed type exerted a considerable effect, as evidenced by the reduced growth of seedlings derived from untreated hulled seeds (90.20 ± 27.10 mm; Figure 3a) compared to the dehulled ones (234.18 ± 29.56 mm; Figure 3b). This can be attributed to the faster germination of the dehulled seeds.

The root to shoot ratio (R:S) was calculated to investigate if the treatments may have promoted a more balanced seedling growth and enhanced early root establishment (Figure 3e). A higher R:S ratio was observed in seedlings obtained from hulled seeds compared with dehulled rice. The treatments applied to hulled seeds promoted shoot growth to a greater extent than root growth. In the case of the dehulled rice, water soaking led to the highest R:S ratio (0.55 ± 0.05).

3.3. Seed Soaking with Elicitors Improved Vigor-Related Indices

The emergence index (EI) was evaluated among the treatments for both hulled and dehulled seeds, as it indicates a weighted cumulative index of emergence (Figure 4a). As evident from previous parameters, significant changes were only identified among the treated hulled rice. In particular, seeds treated with 10 mM FeSO₄ and H₂O₂ (75 mM and 100 mM) displayed an improved EI, with the highest measured value registered for 100 mM H₂O₂.

Similar data were obtained regarding the seedling vigor index (SVI), calculated based on the plant length and the E% at 14 DAS (Figure 4b). All the treatments applied to the hulled seeds resulted in improved SVI values, thus potentially indicating an optimized seedling establishment in the field. Alternatively, none of the treatments were able to improve the SVI in dehulled seeds, but rather a negative effect was observed among the materials obtained from the 1:2500 dilution of *H. scoparia* treatment. When considering the two-way ANOVA, significant *p*-values were registered for all treatments, seed type, and their interaction (Table S3). The untreated hulled seeds presented lower SVI values compared with the dehulled seeds.

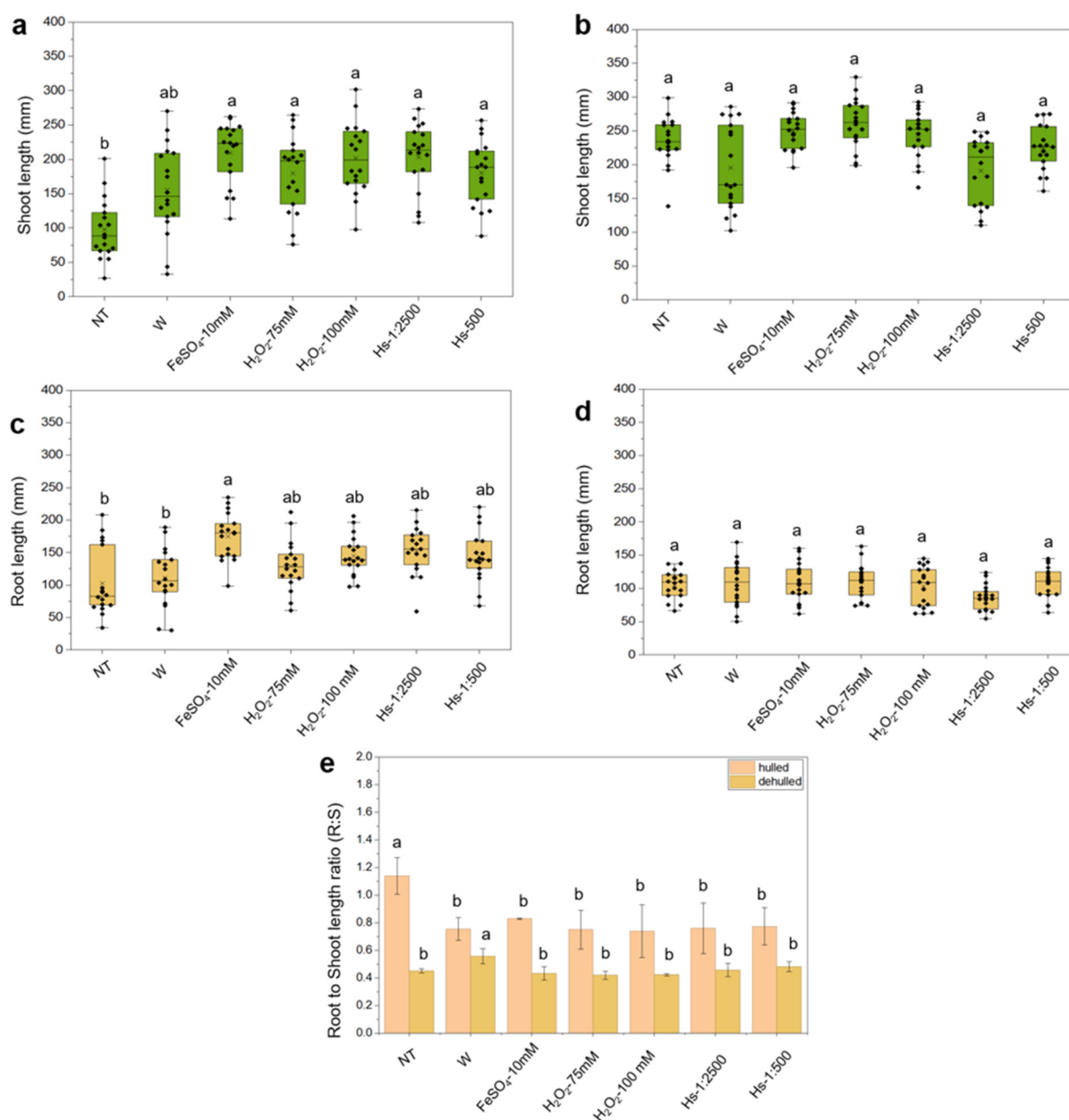


Figure 3. Evaluation of seedling growth from hulled/dehulled rice seeds subjected to soaking treatments with elicitors. (a) Shoot length in seedlings obtained from hulled seeds. (b) Shoot length in seedlings obtained from dehulled seeds. (c) Root length in seedlings obtained from hulled seeds. (d) Root length in seedlings obtained from dehulled seeds. (e) Root-to-shoot ratio (R:S). Statistical differences ($p < 0.05$) were determined by one-way ANOVA with *post hoc* DUNCAN test, conducted separately for hulled and dehulled seeds. Different letters indicate statistically significant differences among samples. The box component of the box-and-whisker plot indicates the interquartile range (25th–75th percentiles); the whiskers represent the 5th–95th percentiles; the “×” symbol denotes the mean; the horizontal line within each box indicates the median; and each diamond represents a data point. NT, non-treated control; W, water soaked; FeSO₄-10 mM, treatment with 10 mM ferrous sulphate heptahydrate solution; H₂O₂-75 mM, treatment with 75 mM hydrogen peroxide solution; H₂O₂-100 mM, treatment with 100 mM hydrogen peroxide solution; Hs-1:2500, treatment with 1:2500 dilution solution of *Hammada scoparia* extract; Hs-1:500, treatment with 1:500 dilution solution of *Hammada scoparia* extract.

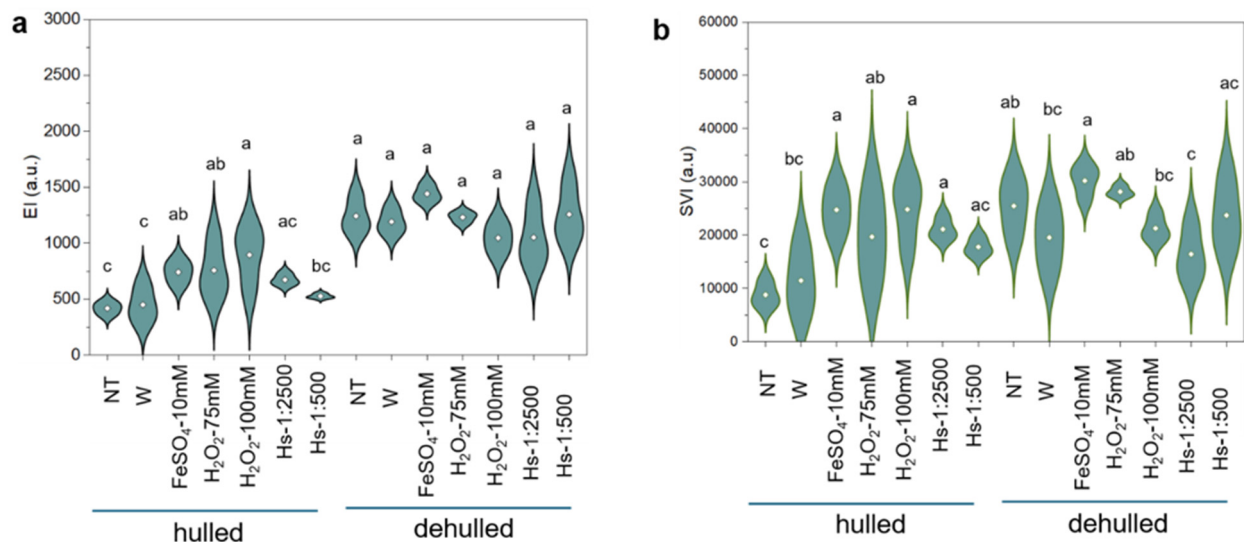


Figure 4. Violin plots representing emergence index (a) and seedling vigor index (b) of Vialone Nano hulled and dehulled seeds subjected to soaking with elicitors. Statistical differences ($p < 0.05$) were determined by one-way ANOVA with *post hoc* DUNCAN test, conducted separately for hulled and dehulled seeds. Different letters indicate statistically significant differences among samples. The white colored diamond within the violin plots indicates the mean values. NT, unprimed control; W, water soaked; FeSO_4 -10 mM, treatment with 10 mM ferrous sulphate heptahydrate solution; H_2O_2 -75 mM, treatment with 75 mM hydrogen peroxide solution; H_2O_2 -100 mM, treatment with 100 mM hydrogen peroxide solution; Hs-1:2500, treatment with 1:2500 dilution solution of *Hammada scoparia* extract; Hs-1:500, treatment with 1:500 dilution solution of *Hammada scoparia* extract.

3.4. Integrative Phenotyping Analyses

An integrated analysis was performed to capture a global overview of the seed treatments effect on the emergence of Vialone Nano hulled and dehulled seeds (Figure 5). Specific data points were considered when generating the individual heatmaps to provide a concise summary with low data noise. Only E% at 14 DAS was selected for the emergence data, while PV from 4 to 6 DAS was used to capture the time points where the highest number of emerged seedlings was recorded. These data points were combined with the EI, MET, Root, Shoot, R:S, and SVI to highlight the seed vigor, emergence speed, and seedling growth. For the hulled seeds (Figure 5a), two distinctive clusters were obtained based on the applied treatments. Specifically, treatments with H_2O_2 (75 mM and 100 mM), 10 mM FeSO_4 , and 1:2500 dilution of *H. scoparia* extract clustered together and separately from NT, W, and 1:500 dilution of *H. scoparia* extract. While the first cluster is relative with specific improvements, the second includes the controls and treatments that had few to no beneficial effect. Among the positive treatments, 100 mM H_2O_2 showed highest improvements in most of the analyzed parameters. In the case of the dehulled seeds (Figure 5b), the clustering pattern was more variegated, indicating that some treatments (e.g., 100 mM H_2O_2 and 1:500 dilution *H. scoparia* extract) presented negative effects compared to NT. Alternatively, treatments that were able to slightly improve germination included 10 mM FeSO_4 and 75 mM H_2O_2 .

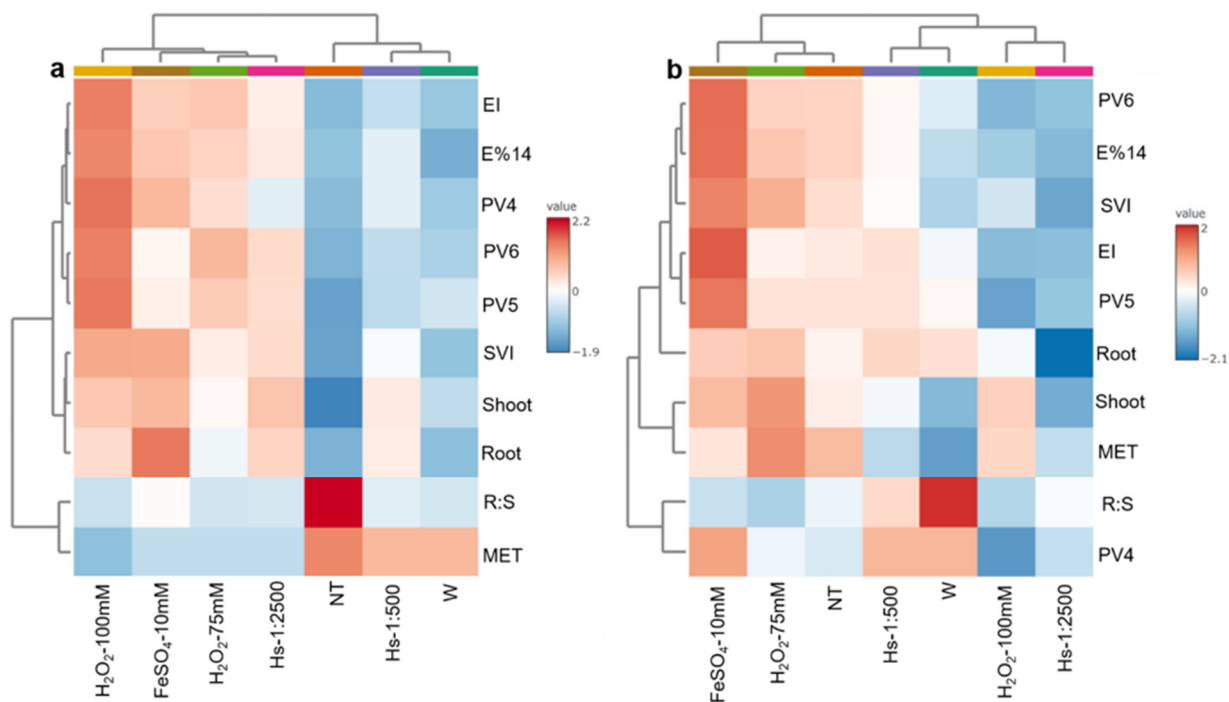


Figure 5. Summary heatmaps grouping the datasets obtained from hulled (a) and dehulled (b) rice seeds. NT, no treatment; W, water soaked; FeSO₄-10 mM, soaking with 10 mM ferrous sulphate heptahydrate solution; H₂O₂-75 mM, soaking with 75 mM hydrogen peroxide solution; H₂O₂-100 mM, soaking with 100 mM hydrogen peroxide solution; Hs-1:2500, soaking with 1:2500 dilution solution of *H. scoparia* extract; soaking with 1:500 dilution solution of *H. scoparia* extract.

4. Discussion

Plant biostimulants, defined as substances or microorganisms that improve nutrient use efficiency, plant growth, stress resilience, and crop quality, are gaining increased attention within the sustainable agriculture approaches [32,33]. This is reflected also in the global biostimulant market, which is undergoing rapid growth and a transition toward more targeted, high-efficiency application methods to mitigate the impacts of climate change [34].

Elicitors applied as seed soaking treatments can function as biostimulants by enhancing the physiological and metabolic processes that support germination and seedling establishment [35–37]. Elicitors include (1) phytohormones and regulators (e.g., gibberellins, abscisic acid, and melatonin), (2) minerals and chemical osmotic agents (e.g., KNO₃, FeCl₃, and PEG), (iii)3) nanomaterials and trace elements (e.g., selenium and zinc oxide nanoparticles), and (4) biostimulants (natural extracts, iron chlorine, and PGPR) [35,36,38–41]. Integrating biostimulants into seed treatments offers a more sustainable approach to optimize germination performance, stress response, and subsequent yield. Among the diverse array of biostimulating agents, natural extracts and biological derivatives have demonstrated significant efficacy when applied as seed treatments [18,27,42]. Seaweed and microalgal extracts (e.g., *Ascophyllum nodosum* and *Ecklonia maxima*), protein hydrolysates, amino acids, humic substances, and plant waste extracts are among the most used [43–46]. These agents trigger physiological and biochemical responses, accelerating starch metabolism via α -amylase activation and enhancing osmotic adjustment and antioxidant systems [47–49].

While elicitors are traditionally recognized for their ability to activate plant defense and stress-response pathways, increasing evidence indicates that when applied at appropriate concentrations, they can also stimulate beneficial physiological responses during early plant development [50–52]. Through controlled seed imbibition, these compounds may

prime cellular metabolism and improve resource mobilization [53]. Such effects can lead to faster and more uniform emergence, ultimately improving seedling establishment.

Although the application of seed treatments is commonly used, several drawbacks are reported, inclusively the fact that they are species-, genotype-, and seed-lot dependent [18,27,54]. This variability necessitates the systematic development and optimization of tailored protocols for distinct genetic materials. Thus, the current work proposes treatments specifically directed to improve seedling emergence in Vialone Nano, a key commercial rice variety in Lombardy. Moreover, this research introduces a novel framework by comparing the responses of hulled and dehulled seeds, an aspect previously underexplored in this context. While the protective husk acts as a barrier against suboptimal conditions and pathogens like *Magnaporthe oryzae* [7], it also enforces seed dormancy by restricting the oxygen and water uptake essential for germination [26].

Based on the performed phenotypic analyses, the use of dehulled seeds significantly accelerated the emergence under controlled soil conditions compared to hulled seeds. This was reflected also in an improved root to shoot ratio and seedling vigor index. These observations can be attributed to the removal of the hull, which acts as a mechanical and chemical barrier. Hull removal facilitates water uptake, increases oxygen availability, and alleviates physical dormancy, collectively influencing early activation of the pre-germinative metabolism [13].

With regard to the tailored seed soaking treatments applied in this work, the integrative multivariate analysis revealed that utilizing FeSO_4 , *H. scoparia* extract, and exogenous H_2O_2 significantly enhanced seedling emergence and early development compared to untreated or water-soaked hulled seeds. For the dehulled seeds, these improvements were minimal given the already enhanced parameters observed with this type of materials. While the efficacy of H_2O_2 and FeSO_4 priming is well documented [27,54–56], the innovative aspects of this work include the addition of *H. scoparia* plant extracts with biostimulant activity. Mostly used as a medicinal plant [57–59], *H. scoparia* is abundant in total phenolics, flavonoids, and specialized alkaloids that present potent antioxidant and free-radical scavenging capabilities. Due to the high concentration of a multitude of secondary metabolites, these extracts need to be highly diluted in order to exert a stimulatory activity. As demonstrated in this study, the application of the most diluted form (1:2500) was beneficial for both hulled and dehulled seeds, while the less diluted solution (1:500) reported negative effects specifically for the dehulled seeds. These results are in line with other works underlining the concentration and duration effect for multiple agents (e.g., selenium, paclobutrazol) [60,61].

In rice, many studies have reported that soaking seeds in water or in nutrient solutions, can speed germination, enhance emergence, and alter metabolism in ways that strengthen early seedlings growths [35,39,60,62,63]. This is driven by a highly coordinated sequence of physiological, metabolic, and biochemical events. For instance, seed soaking has been shown to trigger metabolic activity via gibberellic acid (GA)-mediated signaling pathways [64], mobilization and breakdown of endospermic starch into total soluble sugars [53,65], and modification of the internal redox status and ROS homeostasis [40,66]. Treated seeds presented upregulation in the gene expression and activity of key enzymatic scavengers, including superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), alongside higher accumulation of non-enzymatic osmoprotectants like free proline and glutathione [67,68].

Taken together, these preliminary findings demonstrate that the integration of exogenous agents possessing biostimulant properties, specifically oxidizing agents (H_2O_2), inorganic salts (FeSO_4), and polyphenol-rich botanical extracts (*Hammada scoparia*), holds significant potential to enhance rice seedling emergence kinetics and early vigor.

5. Conclusions

The current study presents a novel, dual-action framework that couples mechanical seed manipulation (via hull removal) with targeted physiological treatments (via seed soaking). The findings of this study demonstrate that while dehulling accelerates seedling emergence in *Oryza sativa* cv. ‘Vialone Nano’, the applied soaking treatments were more effective on the hulled seeds. Combining both hulled and dehulled seeds, the most promising treatments were based on the application of FeSO₄ and H₂O₂. Additionally, we demonstrated that *H. scoparia* extracts can be used as botanical seed biostimulant. Its efficacy is strictly concentration dependent; a highly diluted formulation (1:2500) significantly enhanced germination in both hulled and dehulled seeds, whereas lower dilutions (1:500) may exert phytotoxic effects, particularly on vulnerable, dehulled caryopses.

Overall, the convergence of seed treatments with elicitors represents a promising approach for developing environmentally sustainable agricultural systems. While the treatments developed in this study were tailored specifically to address specific constraints of the Vialone Nano cultivar, their broader applicability remains to be further tested and eventually assessed under field conditions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16136429/s1>, Table S1. Mean values, standard deviations, and significance regarding daily emergence data (E%) relative to the application of seed treatments on hulled and dehulled seeds of Vialone Nano variety; Table S2. Mean values, standard deviations, and significance regarding peak value (PV) data relative to the application of seed treatments on hulled and dehulled seeds of Vialone Nano variety; Table S3. Phenotypic parameters analyzed via two-way ANOVA.

Author Contributions: Conceptualization, A.M. and M.B.; methodology, C.J.D., R.G., E.D. and D.B.; software, M.Z.; validation, E.S., V.M. and M.B.; formal analysis, C.J.D.; investigation, C.J.D.; resources, M.B. and E.S.; data curation, C.J.D.; writing—original draft preparation, A.M. and C.J.D.; writing—review and editing, E.D., E.S. and D.B.; visualization, M.Z.; supervision, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Materials. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Marco Zini, Marco Bains, Edoardo Saluzzo, Valentina Mandrini were employed by Innova-Tech-Agro S.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Tkemaladze, J. Concept of Food Security. *Longev. Horiz.* **2025**, *1*, 1–12. [CrossRef]
2. Prăvălie, R.; Patriche, C.; Borrelli, P.; Panagos, P.; Roșca, B.; Dumitrașcu, M.; Nita, I.A.; Săvulescu, I.; Birsan, M.V.; Bandoc, G. Arable lands under the pressure of multiple land degradation processes. A global perspective. *Environ. Res.* **2021**, *194*, 110697. [CrossRef] [PubMed]
3. FAO. Agricultural Production Statistics-2010–2024. FAOSTAT Analytical Briefs. Available online: <https://openknowledge.fao.org/items/f9b4475e-6e01-4f64-879c-f2606fed2d4b> (accessed on 20 June 2026).
4. Fukagawa, N.K.; Ziska, L.H. Rice: Importance for global nutrition. *J. Nutr. Sci. Vitaminol.* **2019**, *65*, S2–S3. [CrossRef] [PubMed]
5. Elert, E. Rice by the numbers: A good grain. *Nature* **2014**, *514*, S50. [CrossRef] [PubMed]
6. Arcieri, M.; Ghinassi, G. Rice cultivation in Italy under the threat of climatic change: Trends, technologies and research gaps. *Irrig. Drain.* **2020**, *69*, 517–530. [CrossRef]

7. Campos-Soriano, L.; Val, G.; Lupotto, E.; San Segundo, B. Investigation of rice blast development in susceptible and resistant rice cultivars using a GFP-expressing *Magnaporthe oryzae* isolate. *Plant Pathol.* **2013**, *62*, 1030–1037. [\[CrossRef\]](#)
8. Formentin, E.; Sudiro, C.; Ronci, M.B.; Locato, V.; Barizza, E.; Stevanato, P.; Ijaz, B.; Zottini, M.; De Gara, L.; Lo Schiavo, F. H₂O₂ signature and innate antioxidative profile make the difference between sensitivity and tolerance to salt in rice cells. *Front. Plant. Sci.* **2018**, *9*, 01549. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Palanog, A.D.; Mallikarjuna Swamy, B.P.; Shamsudin, N.A.A.; Dixit, S.; Hernandez, J.E.; Boromeo, T.H.; Sta Cruz, P.C.; Kumar, A. Grain yield QTLs with consistent-effect under reproductive-stage drought stress in rice. *Field Crops Res.* **2014**, *161*, 46–54. [\[CrossRef\]](#)
10. Swamy, B.P.M.; Shamsudin, N.A.A.; Rahman, W.; Sta Cruz, M.T.; Kumar, A. Association mapping of yield and yield-related traits under reproductive stage drought stress in rice (*Oryza sativa* L.). *Rice* **2017**, *10*, 21. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Finch-Savage, W.E.; Bassel, G.W. Seed vigour and crop establishment: Extending performance beyond adaptation. *J. Exp. Bot.* **2016**, *67*, 567–591. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Yang, P.; Li, X.; Wang, X.; Chen, H.; Chen, F.; Shen, S. Proteomic analysis of rice (*Oryza sativa*) seeds during germination. *Proteomics* **2007**, *7*, 3358–3368. [\[CrossRef\]](#)
13. Bewley, J.D.; Bradford, K.J.; Hilhorst, H.W.M.; Nonogaki, H. *Seeds: Physiology of Development, Germination and Dormancy*, 3rd ed.; Springer: New York, NY, USA, 2013; pp. 1–397.
14. Bewley, J.D. Seed germination and dormancy. *Plant Cell* **1997**, *9*, 1055. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Paparella, S.; Araújo, S.S.; Rossi, G.; Wijayasinghe, M.A.L.A.K.A.; Carbonera, D.; Balestrazzi, A. Seed priming: State of the art and new perspectives. *Plant Cell Rep.* **2015**, *34*, 1281–1293. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Choudhary, V.K. Seed hydro-priming and in-situ moisture conservation of direct seeded rice: Effects on emergence, productivity, root behaviour and weed competitiveness. *Proc. Natl. Acad. Sci. USA* **2017**, *87*, 181–191. [\[CrossRef\]](#)
17. Zhang, H.; Zhang, X.; Gao, G.; Ali, I.; Wu, X.; Tang, M.; Chen, L.; Jiang, L.; Liang, T. Effects of various seed priming on morphological, physiological, and biochemical traits of rice under chilling stress. *Front. Plant Sci.* **2023**, *14*, 1146285. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Dueñas, C., Jr.; Calvio, C.; Slamet-Loedin, I.H.; Susanto, U.; Macovei, A. Seed Priming with poly-gamma-glutamic acid (γ -PGA) improves rice germination performance under drought conditions. *Agriculture* **2024**, *14*, 926. [\[CrossRef\]](#)
19. Zhang, Y.; Sultan, H.; Shah, A.; Mu, Y.; Li, Y.; Li, L.; Huang, Z.; Song, S.; Tao, Y.; Zhou, Z.; et al. Regulation effect of seed priming on sowing rate of direct seeding of rice under salt stress. *Front. Plant Sci.* **2025**, *16*, 1541736. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Farooq, M.; Usman, M.; Nadeem, F.; Rehman, H.; Wahid, A.; Basra, S.M.A.; Siddique, K.H.M. Seed priming in field crops: Potential benefits, adoption and challenges. *Crop Pasture Sci.* **2019**, *70*, 731–771. [\[CrossRef\]](#)
21. Lutts, S.; Benincasa, P.; Wojtyla, L.S.S.K.; Pace, R.; Lechowska, K.; Quinet, M.; Malgorzata Garnczarska, M. Seed priming: New comprehensive approaches for an old empirical technique. In *New Challenges in Seed Biology—Basic and Translational Research Driving Seed Technology*; Araujo, S., Balestrazzi, A., Eds.; IntechOpen: London, UK, 2016. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Ella, E.S.; Dionisio-Sese, M.L.; Ismail, A.M. Seed pre-treatment in rice reduces damage, enhances carbohydrate mobilization and improves emergence and seedling establishment under flooded conditions. *AoB Plants* **2011**, *2011*, plr007. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Habibi, N.; Parneel, Terada, N.; Pachakkil, B.; Sanada, A.; Kamata, A.; Koshio, K. Effect of priming treatment on improving germination and seedling performance of aged and iron-coated rice seeds aiming for direct sowing. *Plants* **2025**, *14*, 1683. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Jony, M.A.H.; Sarkar, B.C.; Upama, S.A.; Kheya, S.A.; Islam, M.S.; Zaman, F.; Hasan, A.K. Seed Priming Improves Rice Seed Tolerance to Salinity Stress: Unveiling Through Multivariate Analysis. *Seeds* **2026**, *5*, 25. [\[CrossRef\]](#)
25. Yoshida, S. *Fundamentals of Rice Crop Science*, 1st ed.; International Rice Research Institute: Los Baños Laguna, Philippines, 1981; pp. 1–267.
26. Barik, J.K.; Mohapatra, P.K.; Pradhan, S.K.; Kariali, E. De-hulling facilitates seed germination and ethylene production in dormant and non-dormant rice genotypes. *J. Agric. Sci.* **2017**, *155*, 1584–1593. [\[CrossRef\]](#)
27. Dueñas, C., Jr.; Pagano, A.; Calvio, C.; Srikanthan, D.S.; Slamet-Loedin, I.; Balestrazzi, A.; Macovei, A. Genotype-specific germination behavior induced by sustainable priming techniques in response to water deprivation stress in rice. *Front. Plant Sci.* **2024**, *15*, 1344383. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Gupta, K.; Sengupta, A.; Chakraborty, M.; Gupta, B. Hydrogen peroxide and polyamines act as double edged swords in plant abiotic stress responses. *Front Plant Sci.* **2016**, *7*, 1343. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Jiang, Z.; Sung, J.; Wang, X.; Zhang, Y.; Wang, Y.; Zhou, H.; Wen, L. A review on the phytochemistry and pharmacology of the herb *Scoparia dulcis* L. for the potential treatment of metabolic syndrome. *RSC Adv.* **2021**, *11*, 31235–31259. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Tlili, H.; Hanen, N.; Ben Arfa, A.; Neffati, M.; Boubakri, A.; Buonocore, D.; Dossena, M.; Verri, M.; Doria, E. Biochemical profile and in vitro biological activities of extracts from seven folk medicinal plants growing wild in southern Tunisia. *PLoS ONE* **2019**, *14*, e0213049. [\[CrossRef\]](#) [\[PubMed\]](#)

31. Assaad, H.I.; Hou, Y.; Zhou, L.; Carroll, R.J.; Wu, G. Rapid publication-ready MS-Word tables for two-way ANOVA. *Springerplus* **2015**, *4*, 33. [[CrossRef](#)] [[PubMed](#)]
32. Jia, Y.; Kang, L.; Wu, Y.; Zhou, C.; Li, D.; Li, J.; Pan, C. Review on pesticide abiotic stress over crop health and intervention by various biostimulants. *J. Agric. Food Chem.* **2023**, *71*, 13595–13611. [[CrossRef](#)] [[PubMed](#)]
33. Garg, S.; Nain, P.; Kumar, A.; Joshi, S.; Punetha, H.; Sharma, P.K.; Siddiqui, S.; Alshaharni, M.O.; Algopishi, U.B.; Mittal, A. Next generation plant biostimulants & genome sequencing strategies for sustainable agriculture development. *Front. Microbiol.* **2024**, *15*, 1439561. [[CrossRef](#)] [[PubMed](#)]
34. Arinaitwe, U.; Yabwalo, D.N.; Hangamaisho, A. Unlocking the potential of biostimulants: A review of classification, mode of action, formulations, efficacy, mechanisms, and recommendations for sustainable intensification. *Int. J. Plant Biol.* **2025**, *16*, 122. [[CrossRef](#)]
35. Ali, L.G.; Nulit, R.; Ibrahim, M.H.; Yien, C.Y.S. Enhancement of germination and early seedling growth of rice (*Oryza sativa*) var. FARO44 by seed priming under normal and drought stressed conditions. *J. Plant Nutr.* **2020**, *43*, 1579–1593. [[CrossRef](#)]
36. Yadav, S.P.S.; Adhikari, R.; Paudel, P.; Shah, B.; Pokhrel, S.; Puri, S.; Adhikari, R.; Bhujel, S. Effect of different chemical priming agents on physiological and morphological characteristics of rice (*Oryza sativa* L.). *Heliyon* **2023**, *9*, e22389. [[CrossRef](#)] [[PubMed](#)]
37. Ota, K.; Inoguchi, H.; Mitsunaga, T.; Ashizawa, T. Promotion of germination, rooting, and seedling emergence of rice (*Oryza sativa* L.) by soaking seeds in converter slag suspension before sowing. *Soil Sci. Plant Nutr.* **2024**, *71*, 68–78. [[CrossRef](#)]
38. Ali, L.G.; Nulit, R.; Ibrahim, M.H.; Yien, C.Y.S. Efficacy of KNO₃, SiO₂ and SA priming for improving emergence, seedling growth and antioxidant enzymes of rice (*Oryza sativa*), under drought. *Sci. Rep.* **2021**, *11*, 3864. [[CrossRef](#)] [[PubMed](#)]
39. Hu, F.Q.; Jiang, S.C.; Wang, Z.; Hu, K.; Xie, Y.M.; Zhou, L.; Zhu, J.Q.; Xing, D.Y.; Du, B. Seed priming with selenium: Effects on germination, seedling growth, biochemical attributes, and grain yield in rice growing under flooding conditions. *Plant Direct* **2022**, *6*, e378. [[CrossRef](#)] [[PubMed](#)]
40. Zeng, H.; Liu, M.; Wang, X.; Liu, L.; Wu, H.; Chen, X.; Wang, H.; Shen, Q.; Chen, G.; Wang, Y. Seed-soaking with melatonin for the improvement of seed germination, seedling growth, and the antioxidant defense system under flooding stress. *Agron.* **2022**, *12*, 1918. [[CrossRef](#)]
41. Zhang, K.; Khan, M.N.; Luo, T.; Bi, J.; Hu, L.; Luo, L. Seed priming with gibberellic acid and ethephon improved rice germination under drought stress via reducing oxidative and cellular damage. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 2679–2693. [[CrossRef](#)]
42. Wazeer, H.; Shridhar Gaonkar, S.; Doria, E.; Pagano, A.; Balestrazzi, A.; Macovei, A. Plant-based biostimulants for seeds in the context of circular economy and sustainability. *Plants* **2024**, *13*, 1004. [[CrossRef](#)] [[PubMed](#)]
43. Shukla, P.S.; Mantin, E.G.; Adil, M.; Bajpai, S.; Critchley, A.T.; Prithiviraj, B. *Ascophyllum nodosum*-based biostimulants: Sustainable applications in agriculture for the stimulation of plant growth, stress tolerance, and disease management. *Front. Plant Sci.* **2019**, *10*, 655. [[CrossRef](#)] [[PubMed](#)]
44. Cristofano, F.; El-Nakhel, C.; Roupael, Y. Biostimulant substances for sustainable agriculture: Origin, operating mechanisms and effects on cucurbits, leafy greens, and nightshade vegetables species. *Biomolecules* **2021**, *11*, 1103. [[CrossRef](#)] [[PubMed](#)]
45. Afonso, S.; Oliveira, I.; Guedes, F.; Meyer, A.S.; Gonçalves, B. Glycine betaine and seaweed-based biostimulants improved leaf water status and enhanced photosynthetic activity in sweet cherry trees. *Front. Plant Sci.* **2024**, *15*, 1467376. [[CrossRef](#)] [[PubMed](#)]
46. Wazeer, H.; Zeidan, A.; Allevi, J.; Pagano, A.; Dueñas, C.; Marocco, A.; Stagnati, L.; Doria, E.; Macovei, A. Seed priming with plant waste extracts enhances maize drought tolerance in a genotype-specific manner. *Front. Plant Sci.* **2025**, *16*, 1717255. [[CrossRef](#)] [[PubMed](#)]
47. Pandey, E.; Kumari, R.; Faizan, S.; Verma, P. From stress to strength: Improving fenugreek seed germination under saline conditions with moringa leaf extract priming as a biostimulant approach. *Plant Sci. Int. J. Exp. Plant Biol.* **2025**, *361*, 112806. [[CrossRef](#)] [[PubMed](#)]
48. Wang, W.; Zhang, C.; Zheng, W.; Lv, H.; Li, J.; Liang, B.; Zhou, W. Seed priming with protein hydrolysate promotes seed germination via reserve mobilization, osmolyte accumulation and antioxidant systems under PEG-induced drought stress. *Plant Cell Rep.* **2022**, *41*, 2173–2186. [[CrossRef](#)] [[PubMed](#)]
49. Rady, M.M.; Elkelish, A.; Nady, N.M.; Kusvuran, S.; Kusvuran, A.; Shaaban, A.; Alhaithloul, H.A.S.; Ali, M.A.M.; Abu-Elsaoud, A.M.; François, T.; et al. Role of seed priming using natural biostimulants in reducing salt stress effects by reshaping physio-biochemical and antioxidant defense systems in glycine max seedlings. *Front. Plant Sci.* **2025**, *16*, 1630537. [[CrossRef](#)] [[PubMed](#)]
50. Xie, Y.; Wei, L.; Ji, Y.; Li, S. Seed treatment with iron chlorine E6 enhances germination and seedling growth of rice. *Agriculture* **2022**, *12*, 218. [[CrossRef](#)]
51. Farias, K.S.; Ferreira, M.M.; De Oliveira, I.B.; Dalio, R.J.D.; Pirovani, C.P. The BASIDIN effector of the fungus *Moniliophthora perniciosa* promotes positive effects on the seed germination and seedlings development of *Lactuca sativa*. *Front. Plant Sci.* **2025**, *16*, 1529096. [[CrossRef](#)] [[PubMed](#)]
52. Shri, M.; Pandey, V. Developing in-vitro cultivation techniques for *Psoralea corylifolia* and optimizing seed germination methods to investigate the impact of elicitors on seedling growth. *Sci. Rep.* **2025**, *15*, 15530. [[CrossRef](#)] [[PubMed](#)]

53. Farooq, M.; Barsa, S.M.; Wahid, A. Priming of field-sown rice seed enhances germination, seedling establishment, allometry and yield. *Plant Growth Regul.* **2006**, *49*, 285–294. [\[CrossRef\]](#)
54. Chattha, M.U.; Hassan, M.U.U.; Khan, I.; Nawaz, M.; Shah, A.N.; Sattar, A.; Hashem, M.; Alamri, S.; Aslam, M.T.; Alhaithloul, H.A.S.; et al. Hydrogen peroxide priming alleviates salinity induced toxic effect in maize by improving antioxidant defense system, ionic homeostasis, photosynthetic efficiency and hormonal crosstalk. *Mol. Biol. Rep.* **2022**, *49*, 5611–5624. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Bhardwaj, R.D.; Singh, N.; Sharma, A.; Joshi, R.; Srivastava, P. Hydrogen peroxide regulates antioxidant responses and redox related proteins in drought stressed wheat seedlings. *Physiol. Mol. Biol. Plant Int. J. Funct. Plant Biol.* **2021**, *27*, 151–163. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Suo, W.; Li, L.; Zheng, Y.; Pan, S.; Niu, Y.; Guan, Y. Effect of seed priming with zinc, iron and selenium on the low temperature tolerance of *Nicotiana tabacum* L. during seed germination. *Biochem. Biophys. Res. Commun.* **2024**, *735*, 150806. [\[CrossRef\]](#) [\[PubMed\]](#)
57. Eleroui, M.; Feki, A.; Hamzaoui, A.; Kammoun, I.; Bouhamed, M.; Boudawara, O.; Ben Ayed, I.; Ben Amara, I. Preparation and characterization of a novel hamada scoparia polysaccharide composite films and evaluation of their effect on cutaneous wound healing in rat. *Int. J. Pharm.* **2021**, *608*, 121056. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Bourogaa, E.; Jarraya, R.M.; Nciri, R.; Damak, M.; Elfeki, A. Protective effects of aqueous extract of *Hammada scoparia* against hepatotoxicity induced by ethanol in the rat. *Toxicol. Ind. Health* **2014**, *30*, 113–122. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Benine, C.; Boutlelis, D.A.; Touhami, L.A.; Lanez, E.; Ghemam Amara, D.; Rim, G.; Hanen, N.; Zahnit, W.; Messaoudi, M. Green synthesis, characterization, antioxidant, interaction with DNA/BSA, and investigation of cytotoxicity against MCF-7 cancer cells of zinc oxide nanoparticles using *Hammada scoparia* (Pomel) Iljin extract. *Int. J. Biol. Macromol.* **2025**, *295*, 139709. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Khaliq, A.; Aslam, F.; Matloob, A.; Hussain, S.; Geng, M.; Wahid, A.; Rehman, H.U. Seed priming with selenium: Consequences for emergence, seedling growth, and biochemical attributes of rice. *Biol. Trace Elem. Res.* **2015**, *166*, 236. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Gai, D.; Liu, W.; Liang, J.; Guo, L.; Geng, Y.; Zhang, Q.; Du, J.; Gao, J.; Shao, X. The effects of paclobutrazol seed soaking on biomass production and yield formation in direct-seeded rice. *Agronomy* **2023**, *13*, 1402. [\[CrossRef\]](#)
62. Pereira, E.G.; de Lima, B.R.; Medeiros, L.R.A.; Ribeiro, S.A.; Bucher, C.A.; Santos, L.A.; Fernandes, M.S.; Rossetto, C.A.V. Nutripriming with ammonium nitrate improves emergence and root architecture and promotes an increase in nitrogen content in upland rice seedlings. *Biocatal. Agric. Biotechnol.* **2022**, *42*, 102331. [\[CrossRef\]](#)
63. Rajesh, J.; Samanta, S.; Bordolui, S.K. Impact of nutri-priming on germination dynamics and early seedling vigour in rice. *Int. J. Theor. Appl. Sci.* **2026**, *18*, 10–16. [\[CrossRef\]](#)
64. Nie, L.; Song, S.; Yin, Q.; Zhao, T.; Liu, H.; He, A.; Wang, W. Enhancement in seed priming-induced starch degradation of rice seed under chilling stress via GA-mediated α -amylase expression. *Rice* **2022**, *15*, 19. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Nakao, Y.; Asea, G.; Yoshino, M.; Kojima, N.; Hanada, H.; Miyamoto, K.; Yabuta, S.; Kamioka, R.; Sakagami, J.I. Development of hydropriming techniques for sowing seeds of upland rice in Uganda. *Am. J. Plant Sci.* **2018**, *9*, 2170–2182. [\[CrossRef\]](#)
66. Ma, L.; Wei, J.; Han, G.; Sun, X.; Yang, X. Seed osmopriming with polyethylene glycol (PEG) enhances seed germination and seedling physiological traits of *Coronilla varia* L. under water stress. *PLoS ONE* **2024**, *19*, e0303145. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Hussain, S.; Khan, F.; Cao, W.; Wu, L.; Geng, M. Seed priming alters the production and detoxification of reactive oxygen intermediates in rice seedlings grown under sub-optimal temperature and nutrient supply. *Front. Plant Sci.* **2016**, *7*, 439. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Hu, Q.J.; Chen, M.X.; Song, T.; Cheng, C.L.; Tian, Y.; Hu, J.; Zhang, J.H. Spermidine enhanced the antioxidant capacity of rice seeds during seed aging. *Plant Growth Regul.* **2020**, *91*, 397–406. [\[CrossRef\]](#)

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