Seed Res. 53 (2): 148-156, December, 2025
doi: https://doi.org/10.56093/SR.v53i2.8

Redox-Modulating and Micronutrient-Based Priming Strategies Enhance Germination and Vigour by Improving the Physiological Integrity of Onion Seeds

LAVANYA VIJ, NAVJYOT KAUR* AND RAJINDER SINGH

Punjab Agricultural University, Ludhiana, Punjab-141004, India
*navjyot_grewal@yahoo.com

(Received July 2025; Revised August 2025; Accepted August 2025)

ABSTRACT: Seed priming is a promising technique gaining rapid traction in agriculture for improving seed performance and ultimately crop yields, especially in high value crops such as onion, which often suffer from poor germination, vigour and emergence stand. The current study was designed to evaluate the impact of various redox-modulating salts – ascorbic acid and H_2O_2 and micro-nutrient based salts – $Mg(NO_3)_2$, $ZnSO_4$, $CuSO_4$ and $FeCl_3$ on the germination and physiological responses of onion seeds. Laboratory and field studies were carried out in the year 2021 in a completely randomized design in Seed Physiology Laboratory, Punjab Agricultural University, Ludhiana, Punjab, India. *In-vitro* germination studies documented improved early seedling growth and vigour in the onion seeds primed with 0.5% and 1% ascorbic acid; 0.25% and 0.5% Mg $(NO_3)_2$ and 1% $ZnSO_4$. These improvements could be attributed the reduced electrolyte leakage and electrical conductivity recorded which consequently translated in improved physiological integrity and seed quality in the primed seeds. Differential results were recorded in the field investigations with many lab-tested invigorating priming treatments not performing equivalently. Amongst all, onion seeds primed with 0.5% Mg $(NO_3)_2$ for 9 hours emerged as best performing priming treatment documenting a significant six percent increment (50.67%) in germination as compared to untreated onion seeds (44.67%). Higher concentrations of H_2O_2, $CuSO_4$, $ZnSO_4$ and $FeCl_3$ were found to be detrimental, reflecting their potential to undermine seed germination and vigour through oxidative stress, greater electrolyte leakage, reduced membrane stability and poor seedling performance, thus emphasizing the necessity for careful optimization of species-and environment-specific priming concentration and duration.

Keywords: *Allium cepa*, electrolyte leakage, germination, onion, seed priming, vigour

Abbreviations: Hydrogen peroxide – H_2O_2, Magnesium nitrate – $Mg(NO_3)_2$, Zinc sulphate-$ZnSO_4$, Copper sulphate – $CuSO_4$, Ferric chloride – $FeCl_3$

INTRODUCTION

Onion (*Allium cepa* L.) is the world's second most cultivated vegetable after tomato and holds immense economic and nutritional significance owing to its role in cuisines across the globe. It is an Indian subcontinent native crop immensely valued for its rich nutritive and therapeutic properties – including antioxidant, anti-inflammatory, hypo-cholesterolemic and thrombolytic effects [1]. Though the crop has an exceptionally high demand and high value nature, its cultivation and handling of its propagation material storage – both seeds and onion bulbs, pose a great challenge to farmers and agricultural researchers. Onion seeds have a brief shelf life of 9–12 months. The short seed longevity could be attributed to the high lipid content in onion seeds, which makes them accustomed to retain moisture tightly making them susceptible to rapid deterioration, damaging seed quality during storage [2]. Moreover, onion seeds exhibit poor germination, reduced viability, weak seedling vigour under sub-optimal storage conditions leading to low seedling establishment and subsequently, adversely affecting crop yield and the agricultural profits, presenting a grave concern to the farmers choosing onion as a crop of interest despite it being a high value crop [3].

Seed invigoration techniques such as "seed priming" offer a viable solution to address such agronomic challenges. It is a pre-sowing treatment, referring to controlled hydration of seeds fastening the imbibition of water (phase I), partially activating its metabolic processes, leading them to physiologically active state (phase II) without initiating actual seed germination/emergence (phase III). Seed priming ensures efficient, uniform and fast crop establishment under a variable range of environments while reducing the mean germination time and improving the germination percentage. Various seed

priming techniques include hydropriming, osmopriming, halopriming, hormopriming, thermopriming and solid matrix priming for improving seed germination and seedling vigour [4].

Among various methods, the use of redox-active compounds and micronutrient salts stands out due to their ability to facilitate metabolic reactivation and improved cellular redox homeostasis, thus enabling a robust seedling response under stress. Ascorbic acid directly scavenges reactive oxygen species and hydrogen peroxide at low concentrations acts as a signalling molecule to activate cellular stress responses. Magnesium is essential in energy production and chlorophyll synthesis; zinc stabilises membrane structures, assists in auxin synthesis and is a key component of many integral enzymes; copper forms a key cofactor for electron transport chains and many integral enzymes; iron is indispensable for metabolic activity, photosynthesis, nitrogen fixation and respiration, and thus could be beneficial for overall improved seedling establishment and vigour [5].

Given their significance, there is a notable lack of detailed studies evaluating the effects of micro-nutrient based and/or redox modulating inorganic salts on onion seed germination, vigour and early seedling growth. Additionally, the physiological mechanisms underlying these improvements in germination metrics were investigated and field emergence was subsequently assessed to determine whether the treatments that performed well under laboratory investigations also translated into improved performance in the field. The present study was thus, designed to evaluate and develop effective seed priming strategies to achieve improved crop establishment and productivity under field conditions in low-vigour onion seeds of variety Punjab Naroya.

MATERIALS AND METHODS

Plant material and priming treatments: Fresh onion seeds of the red onion variety Punjab Naroya were procured in 2021 from Office of Director (Seeds), PAU, Ludhiana, Punjab, India following seed harvesting and cleaning. Initial seed testing was performed to assess the germination potential of the seed lot and the tested low-vigour seed lot was selected for further testing *via* priming treatments. Hydropriming duration of 9 hours was standardized as optimal and was used across all priming treatments. Subsequently, seeds were primed using varying concentrations of different salt solutions *viz*., ascorbic acid, hydrogen peroxide (H_2O_2), magnesium nitrate [$Mg(NO_3)_2$], zinc sulphate ($ZnSO_4$), copper sulphate ($CuSO_4$) and ferric chloride ($FeCl_3$). Following laboratory experiments were conducted at the Seed Physiology Laboratory, Office of Director (Seeds), Punjab Agricultural University, Ludhiana, Punjab, India (30°54′ N, 75°48′ E, altitude 247 m above mean sea level).

Seed moisture content: The seed moisture content of all onion seed treatments was estimated using 2g of seeds in a moisture analyzer (AND MX-50) set at 103°C as per the ISTA guidelines for seeds with high oil content [6]. The seed moisture content was obtained in percentage and the average mean of the triplicated data was presented.

***In–vitro* germination studies:** *In–vitro* germination studies of the stored onion seeds were carried out in an incubator (Model CI-10S) at 25±2°C. Germination percentage was estimated using "between the paper" method with 100 seeds arranged uniformly on a moistened germination sheet covered by another germination sheet and wrapped in wax paper for moisture retention and placed upright in an incubator for 12 days. On the 12th day, the total normal germinated seedlings were recorded as germination percentage [6]. Ten representative seedlings were selected and their seedling length was recorded using a centimeter scale. Fresh weight of the same representative ten seedlings was measured using an electronic balance (Model Precisa 310M). Vigour indices were calculated by multiplying the germination (%) to the respective average seedling length for seedling vigour index-I [7] and to the respective fresh weight of the ten seedlings for seedling vigour index-II [8].

Germination speed index (GSI) and mean germination time (MGT) were calculated as per the equations described by AOSA [9] and Ellis and Roberts [10], respectively, with 25 seeds placed on top of the moistened filter paper in Petriplates in an incubator (Model CI-10S) set at 25±2°C in triplicates and expressed in seeds day^{-1} and days respectively. The data on the number of seeds germinated to at least 2mm radicle length was recorded daily and the germinated seeds were removed from the Petriplates.

$$GSI = \left\{\left(\frac{\text{No. of seed germinated}}{\text{First day count}}\right) + \left(\frac{\text{No. of seed germinated}}{\text{Second day count}}\right) + \cdots + \left(\frac{\text{No. of seed germinated}}{\text{Final day count}}\right)\right\}$$

MGT = [Σ (No. of seeds germinated on that respective day × No. of days after germination)] / Total number of seeds germinated

Electrical conductivity: The electrical conductivity of all onion seed treatments was recorded in reference to distilled water as blank following an imbibition of 24 hours in beakers containing 20ml of distilled water in an incubator set up at 25±2°C using a conductivity meter (Systronics Conductivity Meter 304). The electrical conductivity was calculated using the equation presented [6] and represented in the units of $mScm^{-1}g^{-1}$.

$$\text{Electrical conductivity} = \frac{\text{Electrical conductivity of seeds} - \text{Electrical conductivity of DW}}{\text{Weight of seeds}}$$

Statistical analysis: The experimental design of the study was kept as completely randomized design. The mean average value and standard error of the mean (SE) was calculated using Microsoft Excel (2016) and the results were presented in the form of mean ± SE. The best performing treatments were identified based on analysis of variance (ANOVA) at $P \leq 0.05$ using data from twice-repeated germination and physiological assays, each performed in triplicate during 2021.

RESULTS AND DISCUSSION

The present study investigated the influence of various priming treatments on the germination and physiological parameters of primed onion seeds in comparison to control untreated seeds. Seed moisture content plays a crucial role in seed deterioration, particularly in onion seeds, due to their hygroscopic nature and high lipid content [2]. Statistical analysis of seed moisture content across various priming treatments revealed no significant ($P \geq 0.05$) variation compared to the control seeds (Figure 1). This outcome serves as an important physiological validation of an effective seed priming and drying technique, wherein the treated seeds successfully re-attain their original weight and moisture level to enter a viable but quiescent state [11]. Additionally, drying of the primed seeds leads to the synthesis of heat shock proteins and late embryogenesis abundant proteins, which are protective in nature and contribute to improved seed longevity while preserving the benefits of priming [12].

Priming treatments significantly influenced the germination and early seedling growth characteristics of onion seeds. However, no significant improvements were observed in tested treatments except for $Mg(NO_3)_2$. Onion seeds treated with 0.5% $Mg(NO_3)_2$ recorded a significant increase in germination percentage. The highest germination (84.33%) was recorded in seeds primed with 0.5% $Mg(NO_3)_2$, while the greatest seedling length was observed in those primed with 0.25% $Mg(NO_3)_2$ which was statistically at par with 1% $Mg(NO_3)_2$ (Table 1). These results align with previous reports demonstrating improved physiological performance, field emergence, germination speed and seedling vigour following onion seed priming with 0.5% magnesium salt [13]. Similar benefits of $Mg(NO_3)_2$ priming in mustard with increased seed germination, vegetative growth, nitrogen assimilation and yield have been highlighted [14]. This improvement may be due to the combined effects of Mg^{2+} and NO_3^- ions. Although cation absorption occurs predominantly during phase I of imbibition, the long 9-hour priming duration allows sufficient time for NO_3^- transport and utilization, thereby supporting healthy seedling establishment and growth.

No significant enhancement in final germination percentage was observed in onion seeds primed with micronutrient salts such as $ZnSO_4$, $FeCl_3$ and H_2O_2 (Tables 1–3). Nevertheless, a marginal improvement in seedling length, fresh weight and vigour indices was

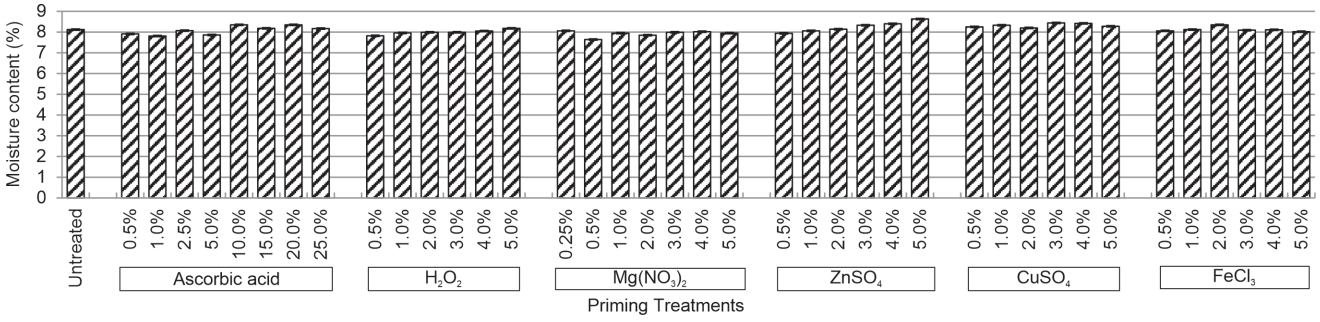

Figure 1. Effect of seed priming on the seed moisture content (%) of onion seeds (var. Punjab Naroya). All the treatments were statistically analysed to be non-significant ($P \geq 0.05$)

recorded at lower concentrations, particularly with 0.5–1% ascorbic acid, 0.5–2% H_2O_2, 0.5–3% $ZnSO_4$ and 0.5–1% $FeCl_3$. These responses indicate that while these treatments may exert limited stimulatory effects on post-germinative growth, they failed to positively influence the critical parameter of germination percentage.

Contrary to the present findings, Ahmed *et al*. [15] reported enhanced germination speed, seedling growth and establishment in maize seeds primed with 40 mL L^{-1} H_2O_2, which was attributed to improved antioxidative enzyme activity under low-temperature stress. Similarly, $CuSO_4$ priming at 0.1% has been reported to significantly improve germination and seed emergence in maize [16]. Such discrepancies highlight strong species-specific and concentration-dependent responses to priming agents. In the present study, the inability of these treatments to enhance germination suggests that their beneficial effects were either insufficient or overridden by stress-induced inhibition in onion seeds.

These differential responses may be partially explained by the phenomenon often described as “hormesis,” wherein low-intensity stress elicits a stimulatory response while higher stress levels are inhibitory [17]. However, the present results do not fully align with classical hormesis, as a slight enhancement in seedling length was accompanied by a reduction in germination. This suggests a phase-specific sensitivity, where early germination processes are more vulnerable to stress than subsequent seedling elongation. Such responses cannot be considered agronomically advantageous, particularly in onion, where rapid loss of viability and germination within 9–12 months after harvest is a well-documented constraint [2].

At higher concentrations, all salt-based priming treatments caused a pronounced decline in germination, seedling fresh weight and vigour indices I and II (Tables 1–3). These inhibitory effects can be attributed to excessive ionic and osmotic stress, leading to membrane destabilization, enzyme inhibition, impaired mitochondrial function and overproduction of reactive oxygen species (ROS). Such disruptions compromise cellular homeostasis and repair mechanisms, ultimately resulting in poor seed performance [18].

Priming treatments also exerted differential effects on germination kinetics. Control seeds exhibited the highest germination speed index (GSI) and the lowest mean germination time (MGT), indicating rapid and synchronized germination. None of the priming treatments surpassed the control in germination speed, although seeds primed with ascorbic acid at 0.5–3% were statistically at par with the control (Table 1). Similar observations have been reported in maize, where ascorbic acid priming improved seedling growth without significantly accelerating germination speed under non-stress conditions [15].

In contrast, H_2O_2-primed seeds showed a marked decline in GSI and a concomitant increase in MGT with increasing concentration (Table 1). This response reflects the dual role of H_2O_2 as both a signalling molecule and a potent oxidant. While low levels may trigger stress-responsive pathways, higher concentrations can induce oxidative damage, programmed cell death in aleurone tissues and impaired endosperm weakening, collectively restricting germination [18]. Comparable reductions in germination kinetics were also observed at higher concentrations of micronutrient salts, likely due to ion toxicity and osmotic imbalance.

Field emergence data further substantiated the laboratory findings. Seeds primed with 0.5% $Mg(NO_3)_2$ recorded the highest field emergence (50.67%), representing a significant six percent increase over control seeds (44.67%) (Figure 2). This treatment was statistically at par with other $Mg(NO_3)_2$ concentrations and corroborates earlier reports of improved physiological performance and stand establishment in magnesium-primed onion seeds [13]. In contrast, all other priming treatments resulted in significantly lower field emergence than the control, underscoring the limited translational value of laboratory gains observed with those treatments. Similar inconsistencies between laboratory vigour enhancement and field emergence have been reported earlier in maize and onion [15,19].

Electrolyte leakage analysis revealed that most priming treatments significantly reduced electrical conductivity relative to the control indicating improved membrane integrity. Among redox-based treatments, 1% ascorbic acid priming resulted in the lowest electrical conductivity and was associated with improved germination-related traits. This effect can be attributed to the antioxidative role of ascorbic acid in limiting lipid peroxidation and preserving embryo cell ultrastructure, thereby enhancing seed vigour and storability [20].

Micronutrient-based priming, particularly with $Mg(NO_3)_2$ at 0.25% and 0.5%, also significantly reduced electrolyte leakage, providing a physiological basis for the improved

Table 1. Effect of seed priming with ascorbic acid and hydrogen peroxide (H_2O_2) on seed germination, seedling vigour and electrical conductivity in onion seeds (var. Punjab Naroya)

Treatments	Germination (%)	Seedling length (cm)	Seedling vigour index-I	Fresh weight of ten seedlings (g)	Seedling vigour index-II	Germination speed index (seeds/day)	Mean germination time (days)	Electrical conductivity ($mScm^{-1}g^{-1}$)
Priming with ascorbic acid								
Control	78.00±0.73	12.31±0.39	960.02±29.40	0.43±0.01	33.59±0.72	6.03±0.18	4.11±0.09	0.302±0.018
0.5% Ascorbic acid	78.00±2.02	13.58±0.61	1060.40±39.93	0.46±0.01	35.77±1.19	5.78±0.23	4.27±0.19	0.242±0.069
1.0% Ascorbic acid	78.00±1.88	14.37±0.48	1118.06±27.60	0.49±0.01	38.08±1.21	5.68±0.27	4.40±0.21	0.093±0.001
2.5% Ascorbic acid	71.42±2.35	12.43±0.22	882.46±19.25	0.46±0.01	32.87±1.39	5.46±0.44	4.45±0.34	0.104±0.001
5.0% Ascorbic acid	70.75±2.81	13.16±0.17	935.79±30.85	0.47±0.01	33.26±2.12	5.75±0.06	4.40±0.05	0.125±0.021
10.0% Ascorbic acid	70.17±2.57	12.75±0.20	899.35±18.23	0.46±0.01	32.58±1.58	5.02±0.02	4.39±0.11	0.163±0.021
15.0% Ascorbic acid	68.67±2.73	12.86±0.38	879.88±40.65	0.44±0.01	30.12±1.70	4.93±0.18	5.19±0.04	0.256±0.020
20.0% Ascorbic acid	67.50±2.59	12.57±0.25	846.67±24.81	0.42±0.02	28.24±1.15	4.73±0.18	5.01±0.09	0.388±0.007
25.0% Ascorbic acid	68.00±3.22	12.49±0.35	840.81±19.06	0.43±0.01	29.29±1.27	3.15±0.17	5.81±0.24	0.554±0.023
LSD ($P \leq 0.05$)	7.45	1.04	82.53	0.03	4.06	0.64	0.50	0.080
Priming with H_2O_2								
Control	78.00±0.73	12.31±0.39	960.02±29.40	0.43±0.011	33.59±0.72	6.03±0.18	4.11±0.09	0.302±0.018
0.5 % H_2O_2	69.00±1.59	13.22±0.29	913.81±39.05	0.29±0.016	20.32±1.51	5.05±0.31	4.69±0.14	0.448±0.031
1.0 % H_2O_2	62.00±0.97	13.04±0.20	807.79±12.13	0.31±0.004	19.03±0.50	4.35±0.21	4.96±0.01	0.437±0.017
2.0 % H_2O_2	58.67±3.15	12.98±0.02	761.48±41.51	0.30±0.005	17.60±1.25	4.03±0.12	5.02±0.01	0.430±0.013
3.0 % H_2O_2	57.67±1.12	12.22±0.20	703.80±4.35	0.36±0.013	20.77±0.71	3.51±0.07	4.73±0.14	0.472±0.002
4.0 % H_2O_2	57.33±1.28	11.93±0.36	686.27±35.82	0.30±0.008	17.23±0.19	3.82±0.11	5.52±0.14	0.565±0.005
5.0 % H_2O_2	54.33±2.01	11.80±0.12	639.80±17.44	0.39±0.016	21.05±1.40	3.49±0.13	5.81±0.24	0.734±0.034
LSD ($P \leq 0.05$)	4.98	0.74	83.45	0.03	2.90	0.52	0.38	0.058

Table 2. Effect of seed priming with magnesium nitrate and zinc sulphate on seed germination, seedling vigour and electrical conductivity in onion seeds (var. Punjab Naroya)

Treatments	Germination (%)	Seedling length (cm)	Seedling vigour index-I	Fresh weight of ten seedlings (g)	Seedling vigour index-II	Germination speed index (seeds/day)	Mean germination time (days)	Electrical conductivity ($mScm^{-1}g^{-1}$)
Priming with magnesium nitrate ($Mg(NO_3)_2$)								
Control	78.67±0.67	11.16±0.08	877.94±3.41	0.41±0.01	32.44±0.62	5.09±0.25	4.13±0.07	0.345±0.029
0.25 % $Mg(NO_3)_2$	79.67±0.42	13.69±0.11	1090.68±11.37	0.49±0.01	38.79±0.81	4.35±0.08	5.18±0.24	0.089±0.001
0.5 % $Mg(NO_3)_2$	84.33±0.21	12.29±0.74	1036.20±60.62	0.48±0.01	40.69±0.74	4.73±0.09	4.81±0.08	0.099±0.001
1.0 % $Mg(NO_3)_2$	81.00±0.26	12.54±0.48	1015.13±38.47	0.49±0.01	39.41±0.32	4.27±0.06	5.26±0.16	0.189±0.001
2.0 % $Mg(NO_3)_2$	80.33±0.42	12.07±0.29	968.66±18.56	0.48±0.01	38.78±0.42	4.02±0.11	5.27±0.21	0.215±0.023
3.0 % $Mg(NO_3)_2$	78.33±0.49	11.79±0.38	923.60±29.04	0.49±0.01	38.54±0.45	3.99±0.11	5.32±0.21	0.283±0.051
4.0 % $Mg(NO_3)_2$	78.83±0.54	11.65±0.31	917.77±18.35	0.49±0.01	38.82±0.72	3.99±0.05	5.32±0.21	0.285±0.005
5.0 % $Mg(NO_3)_2$	79.50±0.62	11.18±0.42	888.80±33.17	0.48±0.01	37.89±0.30	4.12±0.08	5.34±0.21	0.290±0.005
LSD ($P \leq 0.05$)	1.37	1.16	90.27	0.02	1.66	0.34	0.53	0.067.
Priming with zinc sulphate ($ZnSO_4$)								
Control	78.67±0.67	11.16±0.08	877.94±3.41	0.41±0.01	32.44±0.62	5.09±0.40	4.13±0.12	0.345±0.029
0.5 % $ZnSO_4$	77.00±0.65	12.31±0.22	947.87±12.47	0.45±0.01	34.65±0.81	4.88±0.19	4.71±0.05	0.159±0.033
1.0 % $ZnSO_4$	77.42±0.78	12.52±0.21	969.32±19.68	0.45±0.01	34.97±0.48	4.80±0.18	4.84±0.23	0.160±0.032
2.0 % $ZnSO_4$	78.17±0.60	12.24±0.09	956.46±11.56	0.43±0.01	33.66±0.86	4.45±0.07	4.72±0.17	0.224±0.028
3.0 % $ZnSO_4$	78.00±0.37	12.32±0.19	960.43±13.49	0.43±0.01	33.54±0.74	4.23±0.09	4.85±0.22	0.257±0.031
4.0 % $ZnSO_4$	74.17±0.40	11.77±0.08	873.09±8.17	0.40±0.01	29.97±0.53	4.27±0.13	5.14±0.23	0.257±0.030
5.0 % $ZnSO_4$	70.67±0.80	11.34±0.08	801.32±4.68	0.39±0.01	27.77±0.54	4.02±0.12	5.28±0.09	0.250±0.031
LSD ($P \leq 0.05$)	1.82	0.49	42.90	0.03	2.86	0.60	0.59	0.096

Table 3. Effect of seed priming with copper sulphate and ferric chloride on seed germination, seedling vigour and electrical conductivity in onion seeds (var. Punjab Naroya)

Treatments	Germination (%)	Seedling length (cm)	Seedling vigour index-I	Fresh weight of ten seedlings (g)	Seedling vigour index-II	Germination speed index (seeds/day)	Mean germination time (days)	Electrical conductivity ($mScm^{-1}g^{-1}$)
Priming with copper sulphate ($CuSO_4$)								
Control	78.67±0.67	11.16±0.08	877.94±3.41	0.41±0.01	32.44±0.62	5.09±0.40	4.13±0.11	0.345±0.029
0.5 % $CuSO_4$	59.33±0.96	9.64±0.52	570.21±25.62	0.42±0.01	24.75±0.78	4.92±0.24	4.55±0.06	0.098±0.001
1.0 % $CuSO_4$	46.75±0.93	9.14±0.50	427.65±26.14	0.37±0.01	17.18±0.28	4.82±0.33	4.61±0.23	0.123±0.026
2.0 % $CuSO_4$	36.33±0.92	8.54±0.56	311.26±24.42	0.36±0.01	13.01±0.28	4.80±0.15	4.75±0.17	0.129±0.033
3.0 % $CuSO_4$	32.50±0.56	6.98±0.10	226.66±3.65	0.34±0.02	10.99±0.37	4.48±0.14	4.96±0.22	0.127±0.031
4.0 % $CuSO_4$	28.17±1.97	6.73±0.12	189.87±14.16	0.31±0.01	8.67±0.57	4.06±0.48	5.15±0.23	0.191±0.001
5.0 % $CuSO_4$	27.50±4.79	5.51±0.27	156.45±32.43	0.27±0.01	7.24±1.14	3.53±0.16	5.44±0.09	0.224±0.030
LSD ($P \leq 0.05$)	5.99	1.06	61.77	0.03	1.86	0.91	0.43	0.077
Priming with ferric chloride ($FeCl_3$)								
Control	78.67±0.67	11.16±0.08	877.94±3.41	0.41±0.01	32.44±0.62	5.09±0.40	4.13±0.11	0.345±0.029
0.5 % $FeCl_3$	74.17±2.17	11.98±0.12	888.55±29.40	0.43±0.01	31.57±1.39	3.16±0.49	4.27±0.12	0.095±0.002
1.0 % $FeCl_3$	72.83±1.82	12.21±0.27	887.95±22.77	0.43±0.01	31.63±0.88	4.11±0.12	4.72±0.13	0.158±0.061
2.0 % $FeCl_3$	70.25±1.97	11.39±0.09	800.28±22.18	0.40±0.01	28.28±0.87	4.27±0.32	4.90±0.10	0.219±0.081
3.0 % $FeCl_3$	71.00±0.68	11.34±0.10	805.31±12.86	0.40±0.01	28.59±0.27	3.84±0.50	5.14±0.23	0.599±0.083
4.0 % $FeCl_3$	69.67±0.76	11.68±0.17	813.27±14.80	0.39±0.01	27.49±0.95	3.51±0.20	5.39±0.14	0.830±0.137
5.0 % $FeCl_3$	63.75±1.01	11.17±0.15	712.36±17.79	0.39±0.01	24.77±0.71	2.49±0.62	5.87±0.19	0.903±0.059
LSD ($P \leq 0.05$)	4.14	0.53	59.55	0.02	2.52	1.26	0.47	0.232

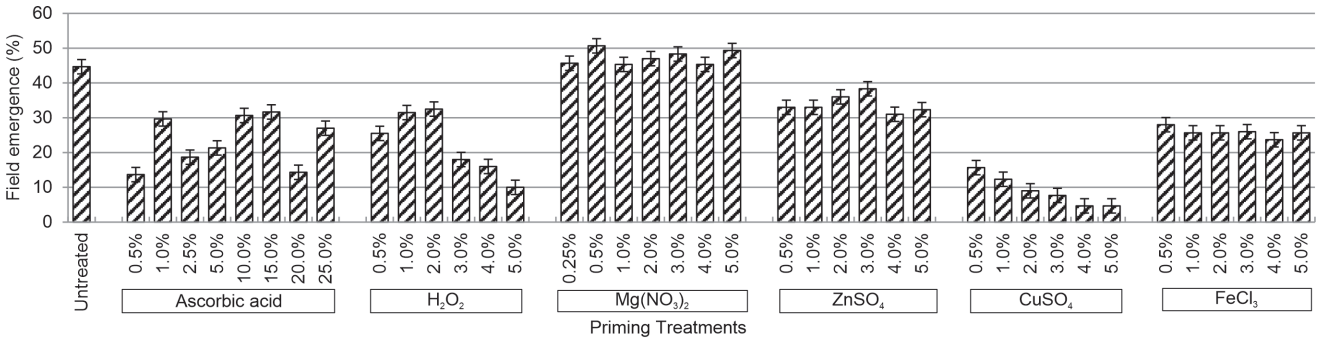

Figure 2. Effect of seed priming on the field emergence (%) of onion seeds (var. Punjab Naroya). Statistical analysis revealed the field emergence of the primed seeds were recorded to be significant ($P \leq 0.05$) accounting L.S.D. value of 4.30, 2.44, 5.37, 3.84, 3.06 and 4.21 for onion seeds primed with ascorbic acid, hydrogen peroxide (H_2O_2), magnesium nitrate ($Mg(NO_3)_2$), zinc sulphate ($ZnSO_4$), copper sulphate ($CuSO_4$) and ferric chloride ($FeCl_3$), respectively

germination, seedling growth and field emergence observed under these treatments. Magnesium plays a central role in energy metabolism, enzyme activation and membrane stabilization, while nitrate contributes to early metabolic reactivation during imbibition, collectively supporting superior seed performance [13].

Although $CuSO_4$, $ZnSO_4$ and $FeCl_3$ priming reduced electrolyte leakage at lower concentrations, these improvements did not translate into enhanced germination or vigour indices (Tables 2 and 3). In contrast, higher concentrations, particularly 3–5% $FeCl_3$, caused excessive electrolyte leakage exceeding that of control seeds, reflecting severe membrane damage and metal toxicity. Similar dose-dependent responses have been documented in fenugreek, where low $FeCl_3$ concentrations enhanced growth, while higher levels induced toxicity symptoms [21]. These findings emphasize the narrow threshold between beneficial and detrimental effects of micronutrient priming.

CONCLUSION

The present study evaluated the effectiveness of redox-modulating and micronutrient-based seed priming strategies in improving germination, vigour and physiological integrity of a low-vigour onion seed lot. The results demonstrated that priming responses were strongly dependent on the type and concentration of the priming agent. While several treatments marginally enhanced post-germinative seedling growth and membrane stability, most failed to improve germination percentage and germination speed, particularly under field conditions.

Among all treatments evaluated, magnesium nitrate emerged as the most effective priming agent. Seed priming with 0.5% $Mg(NO_3)_2$ for 9 hours consistently improved germination attributes, reduced electrolyte leakage, enhanced membrane stability and resulted in significantly higher field emergence compared to untreated seeds. The superiority of $Mg(NO_3)_2$ priming can be attributed to its role in supporting early metabolic activation, membrane stabilization and nutrient availability during germination and seedling establishment.

In contrast, higher concentrations of redox-active and micronutrient salts such as H_2O_2, $ZnSO_4$, $CuSO_4$ and $FeCl_3$ were inhibitory, leading to reduced germination, delayed germination kinetics and increased membrane damage, emphasizing the narrow threshold between beneficial and toxic effects. These findings underscore the importance of optimizing species-specific priming agents, concentrations and durations. Overall, $Mg(NO_3)_2$-based priming offers a simple, cost-effective and physiologically sound strategy to improve seed quality and field establishment in onion, particularly in low-vigour seed lots.

ACKNOWLEDGEMENT

The authors sincerely acknowledge Punjab Agricultural University (PAU), Ludhiana, Punjab, India, for providing necessary laboratory facilities to conduct this research.

REFERENCES

1. SELVI DT AND S SARASWATHY (2017). Seed viability, seed deterioration and seed quality improvements in stored onion seeds: a review. *The Journal of Horticultural Science and Biotechnology*, **93:** 1-7.
2. BRAR NS, P KAUSHIK AND BS DUDI (2019). Effect of seed priming treatment on the physiological quantity of naturally aged onion (*Allium cepa* L.) seeds. *Applied Ecology and Environmental Research*, **18**: 849-862.

3. ZEGEYE MB, TA ALEMU, MA SISAY, SG MULAW AND TW ABATE (2024). Factors affecting onion production: An empirical study in the Raya Kobo district, Amhara regional state, Ethiopia. *Plos One*, **19**: e0305134.

4. SINGH R, VARINDA, L VIJ AND N KAUR (2024). Seed priming: technique, applications and future prospects in vegetable crops. *Seed Research*, **52**: 41-57.

5. TAIZ L, E ZEIGER, IM MOLLER AND A MURPHY (2015). *Plant Physiology and Development*. 6th edition Sinauer Associates Inc., Sunderland, Massachusetts, USA.

6. ISTA (2021). *International Rules for Seed Testing*. International Seed Testing Association, Bassersdorf, Switzerland.

7. ABDUL–BAKI AA AND JD ANDERSON (1973). Vigour determination in soybean seeds by multiple criteria. *Crop Science*, **13**: 630-633.

8. HUANG K, X DAI, Y XU, S DANG, T SHI, J SUN AND K WANG (2018). Relation between level of autumn dormancy and salt tolerance in lucerne (*Medicago sativa*). *Crop and Pasture Science*, **69**: 194-204.

9. AOSA (1983). *Seed Vigor Testing Handbook.* Contribution No. 32 to Handbook on Seed Testing. Association of Official Seed Analysts, Springfield, Illinois, USA.

10. ELLIS RH AND EH ROBERTS (1981). The quantification of ageing and survival in orthodox seeds. *Seed Science and Technol*ogy, **9**: 373-409.

11. VENKATASUBRAMANIAN A AND R UMARANI (2010). Storability of primed seeds of tomato (*Lycopersicon esculentum*), eggplant (*Solanum melongena*), chilli (*Capsicum annum*). *Madras Agricultural Journal*, **97**: 117-124.

12. GONZALEZ-ZERTUCHE L, C VAZQUEZ-YANES, A GAMBOA, SANCHEZ- ME CORONADO, P AGUILERA AND A OROZCO-SEGOVIA (2001). Natural priming of *Wigandia urens* seeds during burial: effects on germination, growth and protein expression. *Seed Science Research*, **11**: 27-34.

13. PATIL BD, AR AHER, VR AWARI AND MR MANJARE (2021). Effect of seed priming on specific activity of acid phosphatase and α–amylase in germinating seeds and correlation study in onion (*Allium cepa* L.). *International Journal of Current Microbiology and Applied Sciences*, **10**: 632-640.

14. BOSE B, R KUMAR, SK KURIL AND HS SRIVASTAVA (2007). Hardening of mustard seeds with magnesium nitrate increase seed germination, vegetative growth, nitrogen assimilation and yield. *Brassica*, **9**: 33-38.

15. AHMAD I, T KHALIQ, A AHMAD, SMA BASRA, Z HASNAIN AND A ALI (2012). Effect of seed priming with ascorbic acid, salicylic acid and hydrogen peroxide on emergence, vigor and antioxidant activities of maize. *African Journal of Biotechnology*, **11**: 1127-1132.

16. FOTI R, K ABURENIA, A TIGEREA, J GOTOSAB AND J GEREC (2008). The efficacy of different seed priming osmotica on the establishment of maize (*Zea mays* L.) caryopses. *Journal of Arid Environments*, **72**: 1127-1130.

17. MATTSON MP (2007). Hormesis defined. *Ageing Research Reviews*, **7**: 1-7.

18. WOJTYLA L, K LECHOWSKA, S KUBALA AND M GARNCZARSKA (2016). Different modes of hydrogen peroxide action during seed germination. *Frontiers in Plant Science*, **7**: 66.

19. ALUKOM, OJ AYODELE, AE SALAMI AND OE OLALEYE (2020). Seed priming technique as innovation to improve germination in onion (*Allium cepa* L.). *Middle East Journal of Applied Sciences*, **10**: 7-17.

20. YAN HF, FS XIA, Y SUN AND PS MAO (2015). Protective effect of ascorbic acid on seedling growth and embryo cellular ultrastructure in aged *Elymus sibiricus* seeds. *Seed Science and Technology*, **43**: 467-479.

21. KAPOOR N, A ARYA, MA SIDDIQUI, H KUMAR AND A AMIR (2011). Physiological and biochemical changes during seed deterioration in aged seeds of rice (*Oryza sativa* L.). *American Journal of Plant Physiology*, **6**: 28-35.