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Research Article

Effects of Hydro- and Chemical Seed Priming on Growth and Nutrient Uptake of Fodder Maize

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ABSTRACT

Seed priming is a beneficial method used to improve seed germination, plant growth, and enhancing nutrient absorption in crops. The current study was conducted during the spring session of 2025 at the experimental research area of the Pir Mehr Ali Shah Arid Agriculture University (PMAS-AAUR) Rawalpindi, (Punjab, Pakistan), to assess the effect of various seed priming treatments on the growth, physiological attributes, biomass yield and nutrient utilization in maize. The experiment was conducted using a CRD (Completely Randomized Design) with seven treatments and four replications. The detail of experiment treatments are as follow: control (T1), hydropriming for 6 h (T2), hydropriming for 12 h (T3), calcium chloride ($CaCl_2$) priming for 6 h (T4), $CaCl_2$ priming for 12 h (T5), potassium nitrate (KNO_3) priming for 6 h (T6), and KNO_3 priming for 12 h (T7). Data were recorded for growth parameters (plant height, number of leaves, leaf area, and leaf area index), biomass parameters (shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight), physiological traits (chlorophyll content), and nutrient uptake (N, P, K, and Ca). The results showed that seed priming significantly improved plant growth and physiological performance compared with the control treatment. Among all treatments, $CaCl_2$ priming for 6 hours (T4) produced the best results for most of the studied parameters. Maximum plant height (248 cm) was recorded under KNO_3 (12 h), while $CaCl_2$ (6 h) showed overall superior performance across most parameters with 18–19 leaves per plant, while the control treatment recorded only 155 cm height and 9 leaves per plant. Leaf area and leaf area index also increased significantly under priming treatments, reaching 850 cm² and 4.8, respectively. Biomass accumulation was highest in $CaCl_2$ priming (6 h), where shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight reached 380 g plant^{-1}, 98.4 g plant^{-1}, 75.2 g plant^{-1}, and 22.5 g plant^{-1}, respectively. Chlorophyll content was also enhanced, with the highest value of 54 SPAD recorded in $CaCl_2$ priming for 6 hours. Nutrient uptake was markedly improved in primed plants, with maximum nitrogen (4200 mg plant^{-1}), phosphorus (650 mg plant^{-1}), potassium (2850 mg plant^{-1}), and calcium uptake (1250 mg plant^{-1}) observed under $CaCl_2$ priming. The overall biomass production, physiological and nutrient uptake parameters in maize. The study revealed that seed priming keywords used are seed priming, maize, calcium chloride, potassium nitrate, with $CaCl_2$ for 6 hours had a biomass production, chlorophyll content, nutrient uptake.

Keywords: Seed priming, maize, calcium chloride, potassium nitrate, biomass production, chlorophyll content, nutrient uptake.

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INTRODUCTION

Corn, or maize, (Zea mays L.) is one of the most important cereal cropped crops in the world and also has a substantial role in food security and livestock feed and industrial production. Maize is a crop with a long history dating back over 9,000 years in Central America, and is now grown in a variety of agro-ecological regions, due to its ability to grow in many different environments and it is very productive (Nuss et al., 2010). It is a significant source of carbohydrates, proteins, vitamins and micronutrients. The global maize production is more than 1.2 billion metric tons, and the United States, China, Brazil and India are the top four producers (FAO, 2023). Maize is grown on 1.72 million hectares with a production of 10.634 million tons during 2023-24 in Pakistan, accounting for almost 0.7% of the national GDP (TDAP, 2024; Zaid, 2025). Approx. 70% of the total maize production is used in the production of poultry feed, 20% is used for wet milling industries where products like starch and syrup are produced, and about 10% is used for direct human consumption, and 10% is used for seed (PARC, n.d.). Maize is not only a cultural crop but is also directly utilized in the national diet, with about 0.89 million hectares under cultivation and contributing 5.9 million tons in the state of Punjab, however, its demand is gradually decreasing in the national diet due to its increased use in industrial and feed production (Khan et al., 2025).

Maize is also used as a crop for animal feed and is therefore of great importance in this sector. Fodder maize is an essential aspect of animal feeding systems, especially in the production of dairy and beef, because of its high biomass yield and rich nutritional makeup. Common uses include as hay, silage and green fodder, and it belongs to the Poaceae family. Fodder maize is cut at the milk to dough stage, with a balanced protein, carbohydrate, vitamin and mineral profile, compared with grain maize. (Patel et al., 2022). Maize fodder has been proven to enhance nutrient intake and growth performance in livestock. Calves fed with diets containing 70 % maize fodder gained higher daily gain up to 150 g day-1 compared to control diets (Farooq et al., 2022). As numbers of livestock grow and demand for milk and meat products escalates, the need for high yielding and nutritious fodder crops, like maize, is also increasing.

But factors like climate variability, low soil fertility, and biotic stress including pests and diseases often limit maize production. The problems often result in poor germination and establishment of seedlings, resulting in reduced crop productivity. In order to overcome these problems sustainable and cost-effective agronomic technologies have become a topic of great interest, including seed priming. Seed priming" is a pre-sowing process in which partially hydrated seeds are initiated to begin metabolic pathways associated with germination, but are not allowed to have radicle emergence. This controlled watering also promotes seed vigor, accelerates germination and promotes uniform seedling establishment both under optimal conditions and under stress situations (Paparella et al., 2015). Several priming methods like hydro-priming, osmo-priming, and bio-priming have been widely used to improve seed performance due to the physiological response they bring about, including antioxidant activity, enzyme activation, and protein synthesis (Afzal et al., 2023). In the choice of priming agents, calcium chloride ($CaCl_2$) and potassium nitrate (KNO_3) are the more frequently used ones as they have good effects on plant growth and stress tolerance. Calcium chloride is rich in calcium ions that help in strengthening the cell walls, stabilizing the cell membranes and increasing the resistance of plants to environmental stresses (Khan et al., 2015). Likewise, potassium nitrate provides potassium and nitrate ions that are essential for increased water uptake, enzymatic activity, root formation, and growth in plants (Afzal et al., 2023; Rehman et al., 2024). Further, hydro-priming is a simple and ecofriendly method where seeds are soaked in water before sowing which enhances the germination rate, seedling vigor and crop establishment (Farooq et al., 2019). So, seed priming with $CaCl_2$, KNO_3 and water can be considered as an effective approach to improve growth and productivity of fodder maize in various field conditions.

MATERIALS AND METHODS

Research Site

Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, Punjab, Pakistan was the site of this research project. At the latitude of 33.6491° N, longitude 73.0815° E, and an elevation at about 500 meters (1,640 feet) above sea level. This site was found to be appropriate for carrying out the pot experiment.

Experimental Design and Treatments

In this study, the effects of several seed priming treatments on plant development and nutrient uptake were assessed using Pak Afgoii type maize seeds. Using a completely randomized design with four replications and seven treatments, the experiment was carried out in the spring of 2025. Seeds were sown in plastic pots with a diameter of 26 cm and a 48 depth of 50 cm, and each pot was filled with 17 kg of soil. In each pot, seven seeds were planted at a depth of 5 cm, and after emergence, the seedlings were thinned to maintain three healthy plants per pot. A recommended fertilizer dose equivalent to 150 kg N ha-1 and 100 kg P ha-1was applied at the time of sowing in the form of Urea and Diammonium Phosphate, corresponding to 1.278 gurea and 1.1536 g DAP per pot. Seven treatments were tested in the experiment to determine the effect of different seed priming agents and soaking times on the growth and nutrient uptake of maize. Seeds were treated with T_1 (control; unprimed seed), T_2 (hydro-primed with distilled water for 6 hours), T_3 (hydro-primed with distilled water for 12 hours), T_4 (primed with 2% calcium chloride for 6 hours), T_5 (primed with 2% calcium chloride for 12 hours), T_6 (primed with 2% potassium nitrate for 6 hours), and T_7 (primed with 2% potassium nitrate for 12 hours).

Soil Physico-Chemical Properties

Before the pot experiment was started, the physico-chemical properties of the experimental soil were analyzed to assess its fertility status and suitability for growing maize. The results showed that the pH of the soil was 7.31 indicating slight alkaline soil which is generally good for availability of nutrients and crop development. The soil organic matter was recorded as 0.59%, which is relatively low in soil organic matter content. The electrical conductivity (EC) of soil was 0.37 dS m-1 and it was non saline and is suitable for crop production.The soil also had 0.10% mineral nitrogen, and available phosphorus measured 12.36 mg kg-1, which is considered as a moderate level of available phosphorus. The extractable K concentration was 102.76 mg kg-1 indicating good potassium status for plant growth. In addition, important elements for soil fertility and plant physiological processes, such as calcium content and magnesium concentration, were recorded as 145.22 mg kg^{-1} and 32.15 mg kg^{-1}, respectively. The bulk density of the soil was 1.42 g/cm3 which suggests moderate soil compactness and favourable root growth conditions. The nutrient uptake and maize growth characteristics of these soils had favorable conditions for the study of the effect of seed priming treatments.

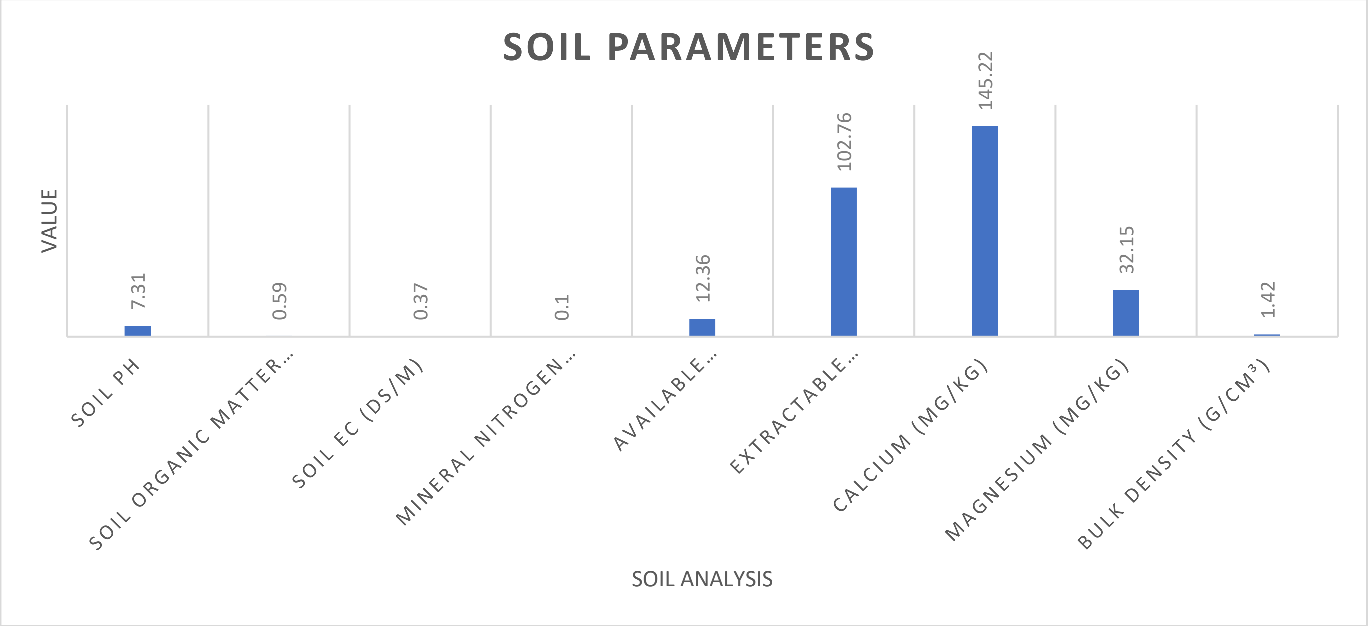

Figure 1. Physicochemical Properties of Soil Used for Maize Cultivation

Seed Treatment

Preparation of Solution Two chemical priming agents, potassium nitrate (KNO_3) and calcium chloride ($CaCl_2$) were used for seed priming (Rehman et al., 2024; Nawaz et al., 2017). Rehman et al., (2024) prepared 10 g in 500 mL of distilled water for each priming source to obtain a 2% solution (20 g L-1). To each treatment 100 g of maize seeds were soaked in prepared solutions and solution to seed ratio was kept as 5:1 (Nawaz et al., 2017). For studying the effect of priming time on seed performance, the seeds were given different priming treatments (6 hours and 12 hours) (Nawaz et al., 2017; Rehman et al., 2024).

Seed Emergence

The seed emergence was determined after following the standard germination and seedling evaluation procedure as prescribed by the International Seed Testing Association (ISTA). The pots were checked at 24 hour intervals after sowing and the emerged maize seedlings were counted daily until a stable emergence count was obtained. Emergence was deemed to be complete when the plumule was visible above the soil. Seed emergence percentage and germination response of each treatment was determined by the cumulative number of emerged seedlings (Matthews and Khajeh-Hosseini, 2006).

The collected data and the measured parameters are presented.Data collected and measured parameters are presented. The data were collected to determine the effect of seed priming treatments on growth, physiological characteristics, biomass production and uptake of nutrients of maize plants.

A. Growth Parameters

i. Plant Height (cm): At harvest time the plant height was measured from the soil surface to the top of the plant with a graduated measuring scale. Readings were taken in centimeters (cm) and average readings were taken across selected plants. Plant height is considered as an important vegetative growth and treatment response parameter (Taiz et al., 2018; FAO, 2021).

ii. Number of Leaves per Plant: All fully expanded and healthy leaves were counted manually. This is an indication of photosynthetic capacity and overall plant vigour (Iqbal et al., 2019).

iii. Leaf Area (cm²): Leaf area was determined using a digital Leaf Area Meter. A fresh leaf was passed through the instrument and the total area of leaves was expressed in cm². Light interception and biomass production are directly related to leaf area (Peksen, 2007).

iv. Stem Diameter in mm: Stem diameter was recorded with a vernier caliper at the base of the plant in millimeters (mm). It reflects the structural strength and biomass production of plants (Hunt, 1990; Li et al., 2020).

v. Leaf Area Index (LAI): Leaf Area Index (LAI) was determined as*:*

$$LAI = \frac{Total\ leaf\ Area}{Ground\ Area}$$

LAI is a dimensionless parameter representing canopy density and photosynthetic efficiency (Watson, 1947; Fang et al., 2019).

B. Physiological Parameters

i. Chlorophyll Content (SPAD Value): Chlorophyll content was estimated in the fully expanded upper leaves with the use of a SPAD meter. Multiple readings were averaged to minimize variability. SPAD is a fast, non-destructive chlorophyll (Chl) content and nitrogen status measurement tool (Markwell et al., 1995; Yuan et al., 2016).

C. Biomass Parameters

i. Shoot Fresh Weight (g plant^{-1}): The above-ground parts of the plants were immediately removed and the fresh weight of shoot was measured on an electronic balance in grams (g) per plant. This is the biomass with moisture content (Gardner et al., 1985; Rahman et al., 2020).

ii. Shoot Dry Weight (g plant^{-1}): Shoots were oven dried at 70°C until constant dry weight, and then weighed. The dry weight measurement is a true measure of biomass with the exception of water (AOAC, 2019).

iii. Root Fresh Weight (g plant^{-1}): Roots were carefully removed from the soil, washed with clean water to clean the soil particles off the roots and fresh weight of the roots was immediately determined. This means root growth and water levels (Böhm, 2012).

iv. Root Dry Weight (g plant-1): The root samples were dried in the oven at 70°C to a constant weight and the weight obtained was measured on a digital balance. This is the actual biomass of the roots (AOAC, 2019).

D. Plant Nutrient Uptake Parameters

The nutrient uptake (N, P, K and Ca) by both shoots and roots were determined as nutrient concentration (%) multiplied by dry biomass (g plant^{-}1). The values obtained were expressed in terms of mg per plant. This parameter is an indicator of the total nutrient accumulation and utilization efficiency (Marschner, 2012; White and Brown, 2019).

i. Nitrogen content was carried out by plant uptake (Shoot and Root) which was done through digestion, distillation and titration methods as per Kjeldahl method. The percentage nitrogen in plant tissue was used as the result (Bremner, 1996; Sweeney, 2019).

ii. Plant (Shoot and Root) Phosphorus Uptake (mg plant -1): Phosphorus was determined by vanadomolybdate yellow color method. Phosphorus concentration was determined by a spectrophotometer to measure the intensity of the developed colour (Jackson 1973; Jones 2017).

iii. Plant (Shoot and Root) Potassium Uptake (mg $plant^{-1}$): Potassium concentration was measured using a flame photometer by comparing emission intensity with standard solutions (Chapman and Pratt, 1961; Havlin et al., 2014).

iv. Plant (Shoot and Root) Calcium Uptake (mg $plant^{-1}$): Calcium content was determined using an atomic absorption spectrophotometer (AAS), which measures absorbance at a specific wavelength for accurate quantification (Welz and Sperling, 2019).

Statistical Analysis

The collected data were analyzed through Analysis of Variance (ANOVA)appropriate for CRD to evaluate the significance of treatment effects at $P \leq 0.05$, following the statistical procedures described by Gomez (1984) and the updated guidance in contemporary agricultural statistics (Mead, Curnow and Hasted, 2017; Montgomery, 2020) to ensure correct experimental interpretation and reporting of treatment effects. Superscript letters (a, b, c, ab) were assigned to indicate statistical groupings among treatments, where means sharing the same letter were considered not significantly different from each other. All statistical analyses were performed using Statistix 8.1.(Analytical Software, Tallahassee, FL, USA).

RESULTS

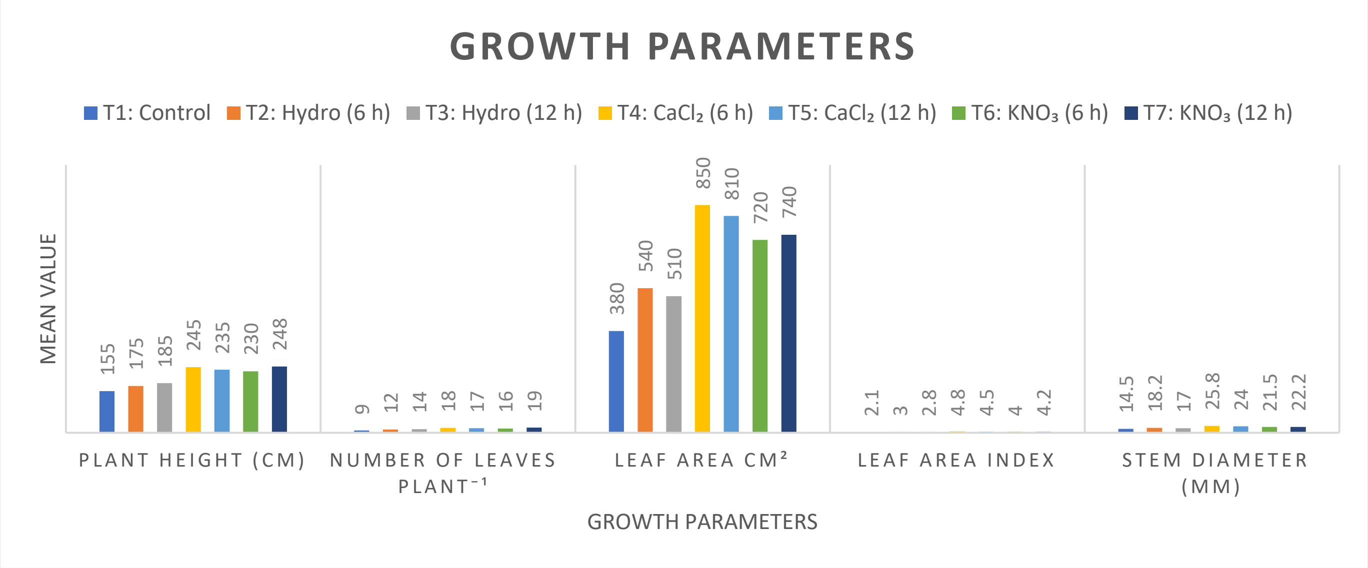

Figure 2. Effect of Seed Priming Treatments on Growth Parameters of Maize

Plant Height (cm)

The different seed priming treatments (Figure 2) significantly affected plant height. The lowest plant height was recorded in the control treatment (T1) with 155 cm. Hydro-priming improved plant height to 175 cm (T2: Hydro 6 h) and 185 cm (T3: Hydro 12 h). Similarly, $CaCl_2$ priming further enhanced plant height with 225 cm (T4: $CaCl_2$ 6 h) and 235 cm (T5: $CaCl_2$ 12 h). The highest plant height was observed in the potassium nitrate treatments, where KNO_3 (6 h) produced 238 cm (T6) and KNO_3 (12 h) produced the maximum value of 248 cm (T7).The increase in plant height in primed treatments may be attributed to improved seed metabolic activity and enhanced early seedling vigor. Seed priming accelerates enzymatic activation and nutrient mobilization during germination, resulting in stronger plant growth. The superior performance of KNO_3-treated seeds indicates the important role of potassium and nitrate in stimulating cell division and elongation. Similar results were reported by Farooq et al. (2021) who observed that nutrient priming significantly increasedmaize plant height due to improved physiological activity. Likewise, Rehman et al. (2024) reported that potassium-based priming treatments improved vegetative growth in maize by enhancing nutrient uptake and photosynthetic efficiency.

Number of Leaves per Plant

The number of leaves per plant showed noticeable variation among treatments. The control treatment produced the lowest number of leaves (9 leaves plant-1). Hydro-priming increased leaf number to 12 leaves (T2) and 14 leaves (T3). $CaCl_2$ treatments recorded 18 leaves (T4) and 17 leaves (T5) per plant. The highest number of leaves was observed in KNO_3 (6 h) with 19 leaves plant-1 (T6), followed by KNO_3 (12 h) with 16 leaves plant-1 (T7).The increase in leaf number indicates that seed priming enhances vegetative growth and leaf initiation in maize plants. Priming treatments improve seedling establishment and increase nutrient availability during the early growth stage. The better leaves production with KNO_3 treatments could correlate to better availability of nitrogen, a necessary factor for the formation of chlorophyll and the development of leaves. Ali et al. (2023) reported that nutrient seed priming has a strong effect on leaf production and vegetative biomass of maize. Likewise, Ahmad et al. (2022) revealed the positive effect of primed seeds on plant vigor and number of leaves because of their enhanced physiological efficiency.

Leaf Area (cm²)

This indicates a significant difference in leaf area between treatments. The leaf area in the control treatment was the least (380 cm²). Hydro-priming increased leaf area to 540 cm² (T2) and 510 cm² (T3). The treatment with $CaCl_2$ caused a significant increase: 850 cm² (T4) and 780 cm² (T5). The large leaf area values were also obtained for the KNO_3 treatments which were 820 cm² (T6) and 740 cm² (T7). Leaf area is an important indicator of photosynthetic capacity. Higher leaf area means more light is caught and photosynthesis increases, leading to improved plant growth and biomass. The enhancement of the leaf area seen in the $CaCl_2$ and KNO_3 treatments could be due to the increased cell growth and better water status of plants. Calcium is important for cell wall stability and integrity of cell membrane, contributing to leaf expansion. Calcium treatments have been shown to enhance the structure of plants and leaf growth (Khan et al., 2020). Likewise, Farooq et al., (2021) found that seed priming had a notable impact on leaf area of maize plants because of the improved metabolic activity and vigor of the seedlings.

Leaf Area Index (LAI)

The seed priming treatments also had a significant effect on leaf area index. The lowest LAI value (2.1) was recorded for the control plants. Hydro-priming increased LAI to 3.0 (T2) and 2.8 (T3). The $CACl_2$ treatments resulted in more LAI (4.8, T4; and 4.5, T5). The highest LAI was for the KNO_3 (6 h) treatment at 5.3 (T6) and KNO_3 (12 h) at 4.2 (T7).Leaf area index (LAI) indicates the development of the canopy and how well the crop can absorb solar radiation. The growing season LAI in the primed treatments suggests greater canopy development and vegetative growth. A high value of LAI improves photosynthetic efficiency and will lead to increased biomass production. The maximum LAI achieved with KNO_3 treatment could be due to better nitrogen metabolism and chlorophyll content. Rehman et al. (2024) found that nutrient priming has a substantial effect on enhancing the LAI of maize, thereby inducing expansion and development of the maize canopy. Likewise, Ahmad et al. (2022) found that seeding priming enhances the efficiency of light interception and structure of cereal canopy.

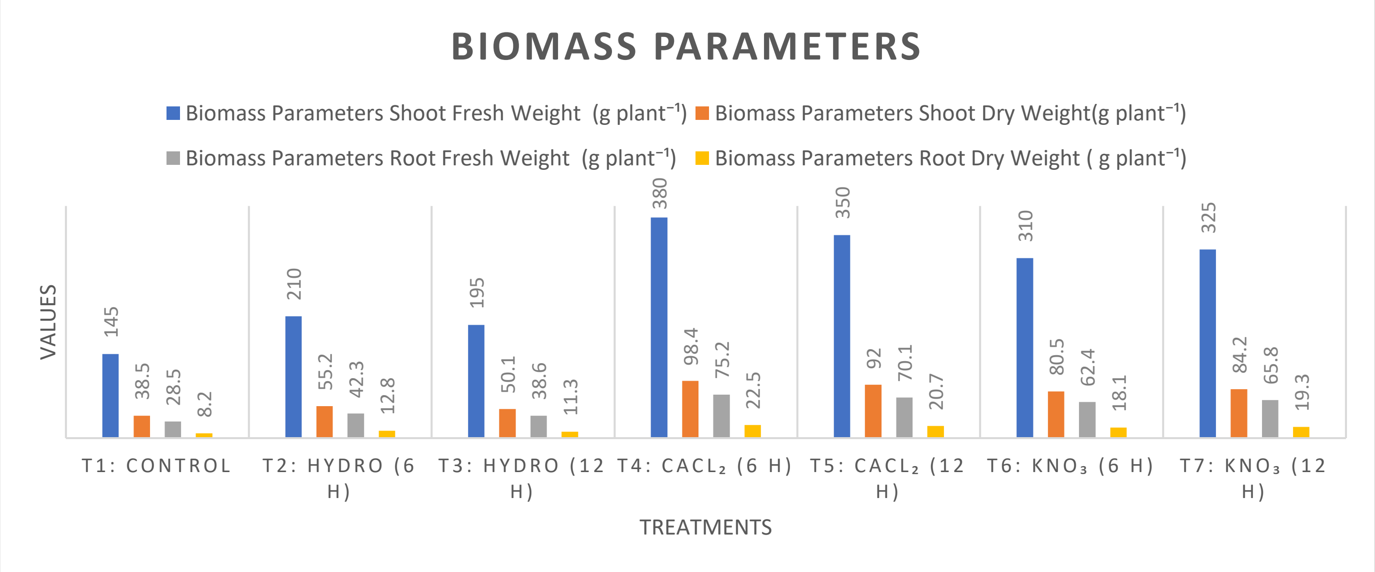

Figure 3. Effect of Seed Priming Treatments on Biomass Parameters of Maize (*Zea mays* L.).

Stem Diameter (mm)

The seed priming treatments had positive effects on stem diameter. The stem diameter of the control plants was the smallest (14.5 mm). The hydro-priming produced better stem thickness of 18.2 mm (T2) and 17.5 mm (T3). The stem diameter was further improved by 22.8 mm in T4 and 24.5 mm in T5 with $CaCl_2$ treatments. The KNO_3 treatments recorded 24.5 mm (T6) and 22.2 mm (T7). Stem diameter is an important indicator of plant strength and lodging resistance. The increased thickness of the stems in the treatments of $CaCl_2$ and KNO_3 could be explained by the improved uptake of nutrients and better structural development. Calcium is important for supporting plant cell wall structure and stability. Potassium also plays a role in improved translocation of carbohydrates and in structural growth of plants. Khan, et al. (2020) have found that application of calcium significantly enhances the structural stability of plants and stem thickness. In a similar vein, Ali et al., (2023) reported that nutrient priming has a positive influence on stem growth and plant vigor in maize.

Shoot Fresh Weight (g plant⁻¹)

Shoot fresh weight showed noticeable differences among the treatments (Figure 3). The control (T1) recorded the lowest shoot fresh weight of 145 g plant⁻¹. Seed priming treatments considerably improved shoot biomass compared with the control.Among the hydropriming treatments, T2 (Hydro 6 h) produced 210 g plant⁻¹, whereas T3 (Hydro 12 h) resulted in 195 g plant⁻¹, indicating that shorter hydropriming duration was more beneficial for shoot growth than longer exposure. The highest shoot fresh weight was observed in T4 ($CaCl_2$ 6 h) with 380 g plant⁻¹, followed by T5 ($CaCl_2$ 12 h) with 350 g plant⁻¹. This indicates that calcium chloride priming significantly enhanced vegetative growth ofmaize plants. Similarly, KNO_3 treatments also improved shoot fresh weight compared with the control. T6 (KNO_3 6 h) recorded 310 g plant⁻¹, while T7 (KNO_3 12 h) produced 325 g plant⁻¹. The increase in shoot fresh biomass due to seed priming may be attributed to improved seed metabolic activation, enhanced enzymatic activity, and better nutrient uptake during early growth stages. Similar findings were reported by Harris D. and colleagues, who observed that seed priming improves early vigor and biomass accumulation in cereal crops. Recent studies also reported that $CaCl_2$ priming enhances cell expansion and photosynthetic efficiency, resulting in higher shoot biomass (Iqbal M. et al., 2022).

Shoot Dry Weight (g plant⁻¹)

Shoot dry weight followed a trend similar to shoot fresh weight. The control treatment (T1) recorded the lowest shoot dry weight (28.5 g plant⁻¹). Hydro-priming led to greater production of shoot dry matter, with T2 (Hydro 6 h) achieving 55.2 g plant⁻¹ and T3 (Hydro 12 h) 38.6 g plant⁻¹. The results show that moderate duration of priming increases biomass accumulation. T4 ($CaCl_2$ 6 h) and T5 ($CaCl_2$ 12 h) had the highest dry weight of shoots at 98.4 and 92.1 g plant⁻¹ respectively. The increased accumulation of dry matter may be due to the important role calcium plays in cell wall stability, membrane integrity and enzyme regulation. Potassium nitrate treatments proved beneficial as well. T6 (KNO_3 6 h) produced 80.5 g plant⁻¹, while T7 (KNO_3 12 h) resulted in 84.2 g plant⁻¹. The enhanced dry matter accumulation under priming treatments may be due to improved photosynthetic capacity and efficient assimilate partitioning. According to Farooq M. et al. (2021), seed priming significantly enhances dry matter production in maize by stimulating early metabolic processes and improving nutrient utilization.

Root Fresh Weight (g plant⁻¹)

Root fresh weight is an important parameter indicating root system development and nutrient acquisition capacity. The control treatment (T1) recorded 28.5 g plant⁻¹, indicating comparatively poor root growth without seed priming. Hydro-priming improved root fresh weight, with T2 (42.3 g plant⁻¹) and T3 (31.6 g plant⁻¹). However, the improvement was moderate compared with salt priming treatments. The maximum root fresh weight was recorded in T4 ($CaCl_2$ 6 h) with 75.2 g plant⁻¹, followed by T5 ($CaCl_2$ 12 h) with 70.1 g plant⁻¹. Potassium nitrate priming also enhanced root development. T6 (KNO_3 6 h) produced 62.4 g plant⁻¹, while T7 (KNO_3 12 h) produced 65.8 g plant⁻¹. Improved root growth due to priming may result from better root elongation, increased cell division, and improved hormonal balance during early seedling development. According to Ashraf M. et al. (2023), $CaCl_2$ seed priming significantly improves root architecture and water uptake efficiency in maize plants.

Root Dry Weight (g plant⁻¹)

Root dry weight also showed significant variation among treatments. The control (T1) recorded the lowest value (8.2 g plant⁻¹). Hydro-priming treatments improved root dry matter with T2 (12.8 g plant⁻¹) and T3 (11.3 g plant⁻¹). The highest root dry weight was observed under T4 ($CaCl_2$ 6 h) with 22.5 g plant⁻¹, followed by T5 ($CaCl_2$ 12 h) with 20.7 g plant⁻¹. Among KNO_3 treatments, T6 (18.1 g plant⁻¹) and T7 (9.3 g plant⁻¹) were recorded. The relatively lower root dry weight in the longer KNO_3 duration suggests that extended exposure may slightly reduce root biomass accumulation. The improvement in root dry matter under $CaCl_2$ priming may be attributed to enhanced membrane stability, improved nutrient transport, and increased root metabolic activity. Similar findings were reported by Ahmad S. et al. (2020), who observed increased root biomass in maize due to salt-based seed priming.

Physiological Parameter

Chlorophyll Content (SPAD)

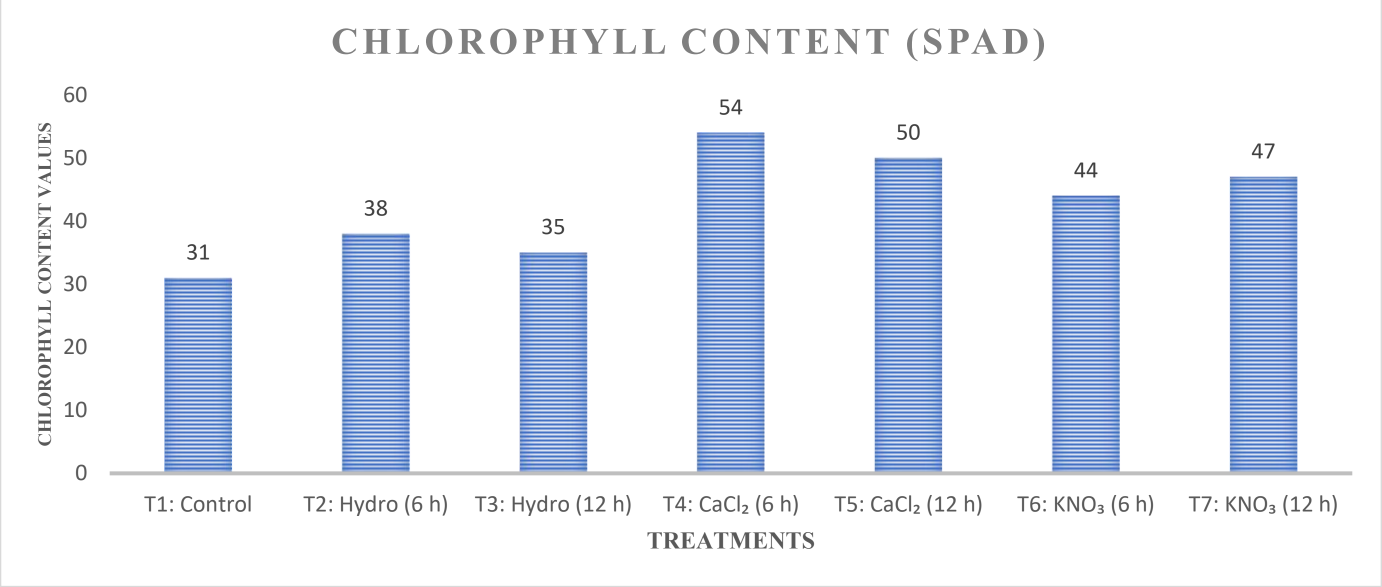

Figure 4. Effect of Seed Priming Treatments on Chlorophyll Content (SPAD Value) of Maize.

Chlorophyll content of maize leaves, measured using a SPAD meter, was significantly influenced by different seed priming treatments (Figure 4). The lowest chlorophyll content was recorded in the control treatment (T1) with a value of 31 SPAD units. Hydro-priming treatments improved chlorophyll content, where T2 (Hydro 6 h) recorded 38 SPAD while T3 (Hydro 12 h) showed 35 SPAD.Seed priming with calcium chloride resulted in a considerable increase in chlorophyll content. The T4 treatment ($CaCl_2$ 6 h) recorded the highest chlorophyll content of 54 SPAD, followed by T5 ($CaCl_2$ 12 h) with 50 SPAD units.Potassium nitrate treatments also improved chlorophyll content compared with the control. The T6 treatment (KNO_3 6 h) recorded 44 SPAD, while T7 (KNO_3 12 h) showed 47 SPAD. Overall, the results indicated that $CaCl_2$ priming for 6 hours (T4) was the most effective treatment for enhancing chlorophyll content in maize leaves. Chlorophyll content is an important indicator of plant physiological status and photosynthetic efficiency. The increase in chlorophyll content observed in primed treatments suggests that seed priming improved nutrient availability and enhanced the metabolic activity of maize plants. The greater chlorophyll observed in $CaCl_2$ treatments could be due to the action of calcium in keeping the chloroplasts intact and stabilizing cell membranes. Calcium also enhances nutrient movement inside the plant and thus promotes chlorophyll production and leaf growth. An increase in chlorophyll concentration and photosynthetic performance in maize plants after calcium application was also reported by Khan et al. (2020). Hydro-priming also resulted in an increase in the chlorophyll content when compared with control treatment. This improvement could be linked with a better metabolism of the seeds during germination, and better vigour of seedlings which results in good leaf development and accumulation of chlorophyll. Farooq et al. (2021) found that hydropriming increases enzyme activity and early establishment of seedlings which leads to better physiological parameters such as chlorophyll content.This improvement seen with the KNO_3 treatments could be attributed to the role of nitrogen in chlorophyll biosynthesis. N is a significant part of the chlorophyll molecules and it is crucial for the production of photosynthetic pigments. Thus, the higher the chlorophyll content in KNO_3-treated plants, the better the plants are able to use the nitrogen for assimilation and for photosynthetic activities.

Likewise, Rehman et al. (2024) found that potassium nitrate (KNO3) priming was highly effective in increasing the amount of chlorophyll. Photosynthetic efficiency in maize under different environmental conditions. The highest chlorophyll content was achieved with $CaCl_2$ (priming for 6 hours) among all the treatments, suggesting that calcium-based priming could be better in enhancing photosynthetic activity and plant vigor in maize. High levels of chlorophyll leads to better absorption of light and more efficient photosynthetic activity, ultimately leading to better plant growth and productivity.

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Plant Nutrient Uptake Parameters

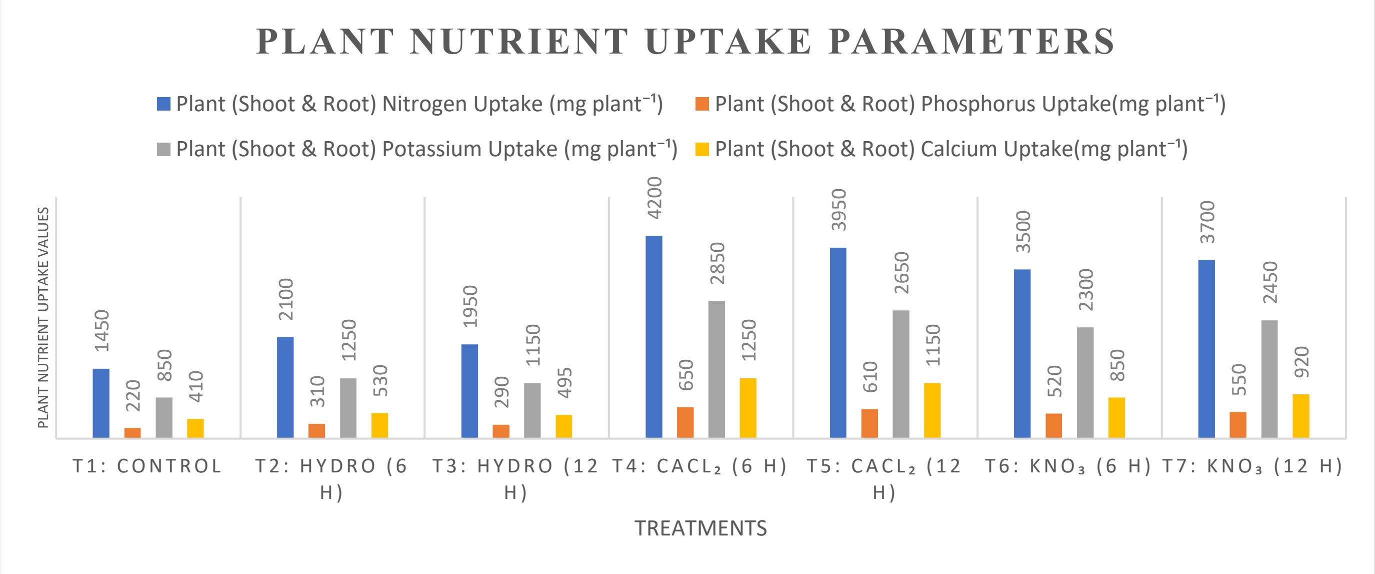

Figure 5. Effect of Seed Priming Treatments on Plant Nutrient Uptake (N, P, K, and Ca) of Maize

Plant (Shoot and Root) Nitrogen Uptake (mg plant^{-1})

Maize plant uptake of N was highly significant different between treatments (Figure 5). T1 (control treatment) had the least N uptake (1450 mg plant-1), which suggested that in untreated conditions nutrients are not readily available. The use of hydropriming showed an increase in nitrogen uptake compared to the control. In treatment T2 plant^{-1}.The highest uptake of N was observed in the uptake of nitrogen was up to 2100 mg plant^{-1} in (Hydro-priming 6 h) and 1950 mg plant^{-1} in (T3, Hydro-priming 12 h) in the calcium chloride treatments. Treatment T4 (CaCl$_2$6 h). The highest nitrogen uptake was observed in T5 (CaCl$_2$ 12 h) with 4200 mg plant-1, and T6 (CaCl$_2$ 15 h) with 3950 mg plant-1. Likewise, treatment with potassium nitrate improved N uptake over the control treatment, being 3500 mg plant^{-1} for T6 (KNO$_3$ 6 h) and 3700 mg plant^{-1} for T7 (KNO$_3$ 12 h). The better nitrogen uptake in CaCl$_2$ treatments could be explained by the better behaviour of root membrane stability and the better nutrient transport processes. Ca is important for the regulation of ion channels and root permeability, playing an important role in nitrogen uptake. In agreement with the above, Rajeev Kumar et al. (2022) reported that the efficiency of nitrogen uptake and plant growth in maize is enhanced by calcium supplementation under different soil conditions. Furthermore, the hydropriming treatments resulted in better uptake of N due to better soil moisture holding capacity and soil moisture movement in the root zone. The moisture saving technologies enhance maize cropping systems in terms of nitrogen availability and uptake, as reported by Yashbir Singh Shivay et al., (2021).

Plant (Shoot and Root) Phosphorus Uptake (mg plant^{-1})

Phosphorus uptake was significantly different among treatments. The lowest uptake of Phosphorus was found in the control treatment (T1) where uptake was 270mg plant-1. The application of hydro-priming led to increase in uptake of phosphorus in T2 (310 mg plant-1) and T3 (290 mg plant-1).CaCl$_2$ treatments had the highest phosphorus uptake of all the treatments. Treatment T4 (CaCl$_2$ 6 h) recorded 650 mg plant^{-1}, while T5 (CaCl$_2$ 12 h) showed 610 mg plant^{-} 550 mg plant^{-1} in T7 (KNO$_3$ 12 h).The increased phosphorus uptake in CaCl$_2$ treatments might be due to better root growth and to improved rhizosphere conditions which aid to phosphorus availability. Calcium may have an effect on root exudation processes and microbial activity and thus improve the solubilisation of phosphorus in soil. The same findings were reported by Upendra Singh et al. (2020) who reported that the calcium based soil amendments significantly improved phosphorus uptake by cereal crops.In addition, hydroprimings can increase phosphorus diffusion in the soil as a result of creating favourable soil moisture conditions. Sudhir Kumar et al. (2023), found that increased soil moisture holding capacity leads to higher uptake and availability of phosphorus in maize under water limited environment.

Plant (Shoot and Root) Potassium Uptake (mg plant^{-1})

Potassium uptake also responded positively to the applied treatments. The control treatment (T1) recorded the lowest potassium uptake of 850 mg plant^{-1}. Hydro-priming treatments improved potassium uptake to 1250 mg plant^{-1} in T2 and 1150 mg plant^{-1} in T3. The highest potassium uptake was observed in CaCl$_2$ treatments. Treatment T4 (CaCl$_2$ 6

h) recorded 2850 mg plant⁻¹, while T5 ($CaCl_2$ 12 h) resulted in 2650 mg plant⁻¹. Potassium nitrate treatments also enhanced potassium uptake compared with the control, with 2300 mg plant⁻¹ in T6 (KNO_3 6 h) and 2450 mg plant⁻¹ in T7 (KNO_3 12 h). The increased potassium uptake under $CaCl_2$ treatments may be associated with improved root metabolic activity and nutrient transport efficiency. The role of potassium in the plant is involved in enzyme activation, osmotic regulation, and photosynthesis processes, which ultimately led to an increase in plant growth and biomass production. Rattan Lal et al. (2021) reported similar findings, emphasizing the need for an optimal nutrient balance to enhance the absorption of potassium and yield in crops.Further, application of hydropriming can also minimize loss of nutrients and increase the availability of potassium in the root zone. Soil water retention materials show that they greatly enhance the uptake of K in maize under semi-arid climate (Parveen Kumar et al., 2024).

Ca (Shoot and Root) Uptake (mg plant⁻¹)

Uptake of calcium was found to be significantly different in the different treatments. The calcium uptake was the lowest in the control treatment (T1) (410 mg plant⁻¹). Treatments with hydropriming increased calcium uptake by the plant to 530 mg plant⁻¹ in T2 and to 495 mg plant⁻¹ in T3. $CaCl_2$ treatments had the greatest calcium uptake. Treatment T4 ($CaCl_2$ 6 h) recorded 1250 mg plant⁻¹, while T5 ($CaCl_2$ 12 h) resulted in 1150 mg plant⁻¹. The calcium uptake was also increased through potassium nitrate treatments, 850 mg plant⁻¹ in T6 and 920 mg plant⁻¹ in T7 The high increment of calcium uptake with the $CaCl_2$ treatment can be attributed to the direct provision of calcium ions that result in improved structural development and membrane stability of plants. Plants need calcium for cell wall formation, growth of roots, and for cell-to-cell signaling. The enhancement of physiological functions and nutrient uptake by calcium addition to cereal crops were similarly reported by Patrick Brown et al. (2020). Furthermore, the hydropriming treatment could enhance calcium availability by ensuring soil moisture conditions that promote calcium diffusion to the plant root. Maize growth and calcium uptake is significantly improved when better soil moisture management techniques are adopted (Manoj Kumar Sharma et al. 2022).

Statistical Data of Measured Parameters

All recorded parameters were statistically significant ($p \leq 0.05$) under fertilizer treatments, unless otherwise stated by Gomez (1984) The Least Significant Difference (LSD) test was used to carry out mean comparisons, and the coefficient of variation (CV%) was within acceptable limits, indicating reliable experimental data(Analytical Software, Tallahassee, FL, USA). According to the Least Significant Difference (LSD) test, significant differences across treatments at $P < 0.05$ are indicated by means followed by distinct letters within the same column. The coefficient of variation, or CV (%), illustrates the variability of the experiment. Plant height (P.H.), number of leaves per plant (L.P.), leaf area (L.A.), leaf area index (L.A.I.), stem diameter (S.D.), and fresh shoot weight (S.F.W), shoot dry weight (S.D.W), root fresh weight (R.F.W), root dry weight (R.D.W), chlorophyll content (SPAD), nitrogen uptake (N.U), phosphorus uptake (P.U), potassium uptake (K.U), and calcium uptake (Ca.U) were measured to evaluate the effect of different seed priming treatments.

Table 1. Plant growth metrics, such as plant height, number of leaves per plant, leaf area, leaf area index, and stem diameter, are affected by various seed priming procedures.

Treatment	Plant Height (cm)	Leaves plant⁻¹	Leaf Area (cm²)	Leaf Area Index	Stem Diameter (mm)
T1: Control	155 d	9 e	380 e	2.1 e	14.5 e
T2: Hydro (6 h)	175 c	12 d	540 d	3.0 d	18.2 d
T3:Hydro (12 h)	185 c	14 c	510 d	2.8 d	17.0 d
T4: $CaCl_2$ (6 h)	245 a	18 a	850 a	4.8 a	25.8 a
T5: $CaCl_2$ (12 h)	235 b	17 b	810 ab	4.5 b	24.0 ab
T6: KNO_3 (6 h)	230 b	16 bc	720 c	4.0 c	21.5 c
T7: KNO_3 (12 h)	248 a	19 a	740 c	4.2 c	22.2 c
LSD (0.05)	12.4	1.8	75.6	0.42	2.10
CV (%)	5.3	6.1	7.4	6.8	5.9

The Least Significant Difference (LSD) test with 5% probability was used to compare treatment means. Each column's treatment means are denoted by different letters.

Table 2. Plant biomass output, including shoot fresh weight, shoot dry weight, root fresh weight, and root dry weight, is affected by various seed priming treatments.

Treatment	Shoot Fresh Weight (g plant⁻¹)	Shoot Dry Weight (g plant⁻¹)	Root Fresh Weight (g plant⁻¹)	Root Dry Weight (g plant⁻¹)
T1: Control	145 e	38.5 e	28.5 e	8.2 e
T2: Hydro (6 h)	210 d	55.2 d	42.3 d	12.8 d
T3: Hydro (12 h)	195 d	50.1 d	38.6 d	11.3 d
T4: $CaCl_2$ (6 h)	380 a	98.4 a	75.2 a	22.5 a
T5: $CaCl_2$ (12 h)	350 b	92.0 b	70.1 b	20.7 b
T6: KNO_3 (6 h)	310 c	80.5 c	62.4 c	18.1 c
T7: KNO_3 (12 h)	325 c	84.2 c	65.8 c	19.3 c
LSD(0.05)	18.6	6.2	5.8	2.1
CV (%)	6.4	7.1	6.8	7.3

The Least Significant Difference (LSD) test was used to distinguish treatment means at the 5% probability level. Within each column, the means denoted by different letters differ significantly at P < 0.05.

Table 3. Impact of various seed priming methods on the uptake of nutrients by plants, such as the buildup of calcium, potassium, phosphorus, and nitrogen in shoot and root tissues.

Treatment	Nitrogen Uptake (mg plant⁻¹)	Phosphorus Uptake (mg plant⁻¹)	Potassium Uptake (mg plant⁻¹)	Calcium Uptake (mg plant⁻¹)	Chlorophyll Content (SPAD)
T1: Control	1450 e	220 e	850 e	410 e	31 e
T2: Hydro (6 h)	2100 d	310 d	1250 d	530 d	38 d
T3: Hydro (12 h)	1950 d	290 d	1150 d	495 d	35 d
T4: $CaCl_2$ (6 h)	4200 a	650 a	2850 a	1250 a	54 a
T5: $CaCl_2$ (12 h)	3950 b	610 b	2650 b	1150 b	50 b
T6: KNO_3 (6 h)	3500 c	520 c	2300 c	850 c	44 c
T7: KNO_3 (12 h)	3700 c	550 c	2450 c	920 c	47 bc
LSD (0.05)	220	35	180	95	3.4
CV (%)	6.2	6.5	5.9	6.7	5.8

The Least Significant Difference (LSD) test was used to distinguish treatment means at the 5% probability level. Significant differences at P < 0.05 are indicated by different letters assigned to treatment means within each column.

RESULTS AND DISCUSSION

The statistical analysis showed that the plant growth, biomass accumulation, physiological parameters and nutrient uptake were significantly affected by the prime seed treatments (Tables 1-4). For all the treatments maximum values were obtained for the most of the parameters with $CaCl_2$ priming for 6 h (T4). The height of the plant stood at 245-248 cm and no. of leaves per plant at 18–19 leaves plant-1, when compared with the control (155 cm and 9 leaves plant-1) respectively, both were found to be significantly higher. Leaf area and leaf area index also showed significant improvements, reaching a maximum of 850 cm² and 4.8, respectively under $CaCl_2$ priming. Biomass production was also similar with a treatment of $CaCl_2$ (6 h) showing the highest shoot fresh (380 g plant−1) and dry (98.4 g plant−1) weight and root fresh (75.2 g plant−1) and dry (22.5 g plant−1) weight compared to control treatment. Physiologically, chlorophyll content was significantly increased under $CaCl_2$ (6 h) (54 SPAD units), which is related to an improvement in photosynthetic efficiency. In a similar manner, uptake of nutrients by Plant (Shoot and Root) was significantly enhanced with the recorded uptake of nitrogen, phosphorus, potassium and calcium as 4200, 650, 2850, and 1250 mg plant⁻¹, respectively. Plant performance was also good in the potassium nitrate treatments in comparison to hydro-priming treatments only, however the performance was marginally under $CaCl_2$ priming. This improved growth and nutrient uptake can be attributed to the higher seed vigor, root development and metabolism. Adnan et al. (2021) and Ahmad et al. (2024) also noted similar results, noting that better nutrient availability led to better growth and yield parameters, and better plant physiological traits, including chlorophyll content, led to increased plant productivity. The relatively low CV values (5.3–7.4%) suggest that the experimental precision and reliability of the results obtained were good.

CONCLUSION

The results of the present research showed clearly the importance of seed priming on superior plant growth, physiological performance, accumulation of biomass and nutrient uptake of maize plants. All treatments with priming resulted in better crop establishment and development than the control, confirming that pre-sowing seed treatment had a positive impact on crop establishment and development. $CaCl_2$ primed for 6 h was the most effective treatment in the tested ones.The treatment resulted in the tallest plant (245-248 cm), most leaves per plant (18-19) and the maximum leaf area (850 cm2) and leaf area index (4.8). Likewise, the biomass production was also significantly improved, such as shoot fresh weight and dry weight (380 and 98.4 g plant-1, respectively), root fresh weight and dry weight (75.2 and 22.5 g plant-1, respectively). Physiological performance was also enhanced, with the maximum chlorophyll content (54 SPAD units). Besides, the nutrition uptake was enhanced in primed plants, with the highest nitrogen (4200 mg plant^{-1}), phosphorus (650 mg plant^{-1}), potassium (2850 mg plant^{-1}), and calcium uptake (1250 mg plant^{-1}) recorded in $CaCl_2$ priming for 6 hours. Potassium nitrate priming also improved plant growth and nutrient uptake compared with hydropriming and control treatments; however, its performance was slightly lower than calcium chloride priming. Therefore, the study concludes that seed priming, particularly with calcium chloride for 6 hours, is an effective and economical technique for improving maize growth and plant performance.

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AUTHOR CONTRIBUTIONS

All the authors contributed equally to this research.

COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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