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Growth Performance and Osmotic Adjustment of Purslane under Various NaCl Salt Stresses

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ABSTRACT

Salinity is one of the most severe abiotic stresses limiting agricultural productivity and plant growth worldwide, particularly in arid and semi-arid regions where salt accumulation in soils adversely affects crop performance (Munns & Tester, 2008). The present study investigated the growth performance and osmotic adjustment mechanisms of purslane (*Portulaca oleracea* L.) under various NaCl-induced salinity stresses. Laboratory germination and net-house pot experiments were conducted at the Institute of Plant Sciences, University of Sindh, Jamshoro, using five salinity treatments: 0, 50, 100, 150, and 200 mM NaCl. The experiments were arranged in a Complete Randomized Design (CRD) with four replications to evaluate germination behavior, vegetative growth, physiological responses, and osmotic adaptation under saline conditions. The results demonstrated that increasing NaCl concentrations significantly reduced germination percentage, plant height, leaf number, fresh and dry biomass, and chlorophyll contents. Severe salinity stress at 150 and 200 mM NaCl markedly inhibited plant growth and photosynthetic pigments, indicating the negative effects of osmotic stress and ion toxicity. However, purslane exhibited substantial physiological adaptation through enhanced accumulation of compatible osmolytes and ionic regulation mechanisms. Proline and soluble carbohydrate concentrations increased progressively with increasing salinity levels, suggesting their important role in osmotic adjustment and stress protection. Similarly, sodium and chloride accumulation increased significantly in plant tissues under higher salinity, whereas potassium concentration declined, resulting in altered ionic balance. Overall, the study revealed that purslane possesses effective osmotic adjustment and physiological defense mechanisms that enable survival under moderate to high salinity conditions. These findings highlight the potential of purslane as a salt-tolerant vegetable crop suitable for cultivation in saline and marginal soils, contributing to sustainable agriculture and improved utilization of salt-affected lands.

Keywords: Purslane (*Portulaca oleracea* L.); Salinity Stress; Osmotic Adjustment; Proline Accumulation; Ion Homeostasis

Introduction

Soil salinity is one of the most serious environmental constraints affecting agricultural productivity and food security worldwide. Rapid increases in soil salinization due to climate change, seawater intrusion, poor irrigation practices, low precipitation, and

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excessive evaporation have significantly reduced the productivity of cultivated lands in both developed and developing countries (Munns & Tester, 2008). It is estimated that more than 20% of irrigated agricultural lands globally are affected by salinity stress, and this proportion is expected to increase continuously in the coming decades (Shrivastava & Kumar, 2015). Salinity stress is particularly severe in arid and semi-arid regions where salt accumulation in the root zone limits crop growth, reduces yield potential, and threatens sustainable agricultural production. In countries such as Pakistan, salinity has become a major obstacle to food security and economic development because large areas of fertile agricultural land are progressively becoming salt affected.

Salinity adversely affects plants through complex physiological, biochemical, and molecular disturbances. The primary effect of excessive salt accumulation is osmotic stress, which reduces soil water potential and limits water uptake by plant roots, resulting in physiological drought conditions even when moisture is available in the soil (Parida & Das, 2005). As salinity increases, plants experience ionic toxicity due to excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions within plant tissues. These toxic ions disrupt membrane integrity, enzyme activities, nutrient transport, and cellular metabolism, thereby impairing plant growth and development (Flowers & Colmer, 2008). Excess sodium accumulation also interferes with potassium uptake, leading to ionic imbalance and reduced metabolic efficiency.

One of the major consequences of salinity stress is the inhibition of photosynthesis due to chlorophyll degradation and damage to chloroplast structures. High salt concentrations reduce chlorophyll synthesis and accelerate pigment degradation, resulting in decreased photosynthetic efficiency and biomass accumulation (Ashraf & Harris, 2013). Salinity stress also stimulates excessive production of reactive oxygen species (ROS), including hydrogen peroxide, superoxide radicals, and hydroxyl ions, which cause oxidative damage to proteins, lipids, nucleic acids, and cellular membranes (Hasanuzzaman et al., 2021). Oxidative stress further disrupts physiological processes and contributes to growth inhibition, premature senescence, and reduced crop productivity under saline environments.

To survive under saline conditions, plants activate several adaptive physiological and biochemical mechanisms that enhance stress tolerance and maintain cellular homeostasis. One of the most important adaptive responses is osmotic adjustment through the accumulation of compatible solutes such as proline, soluble sugars, glycine betaine, and soluble carbohydrates (Acosta-Motos et al., 2017). These osmolytes help maintain cell turgor, stabilize proteins and membranes, and protect cellular structures against dehydration and osmotic damage. Proline accumulation, in particular, is considered a major stress indicator and plays an essential role in osmoprotection, ROS scavenging, membrane stabilization, and enzyme protection under saline conditions (Bates et al., 1973).

Similarly, soluble carbohydrates contribute to osmotic regulation and serve as energy reserves during stress conditions. Accumulation of soluble sugars under salinity stress helps maintain cellular water balance and supports stress adaptation mechanisms. In addition to osmotic adjustment, antioxidant defense systems involving phenolic compounds, flavonoids, and antioxidant enzymes are activated to detoxify reactive

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oxygen species and minimize oxidative damage (Bose et al., 2014). Maintenance of ionic homeostasis through regulation of sodium and potassium transport is another important mechanism of salinity tolerance. Salt-tolerant plants often compartmentalize toxic sodium ions into vacuoles while maintaining adequate potassium concentrations in the cytoplasm to preserve metabolic activities and enzyme functions (Shabala & Mackay, 2011).

Among salt-tolerant vegetable crops, Purslane (*Portulaca oleracea* L.) has attracted increasing scientific attention because of its remarkable adaptability to stressful environmental conditions. Purslane is an annual succulent herb belonging to the family Portulacaceae and is widely distributed in tropical and subtropical regions of the world. It is recognized as a highly nutritious leafy vegetable rich in omega-3 fatty acids, vitamins, minerals, carotenoids, flavonoids, and antioxidant compounds (Petropoulos et al., 2016). In addition to its nutritional value, purslane possesses significant medicinal importance and has traditionally been used in the treatment of inflammation, cardiovascular diseases, gastrointestinal disorders, diabetes, and oxidative stress-related ailments (Zhou et al., 2015).

Purslane is also considered a moderately salt-tolerant halophytic species due to its succulent morphology, efficient osmotic adjustment capacity, and ability to accumulate salts without severe physiological damage. Previous studies have demonstrated that purslane can survive and maintain growth under moderate to high salinity conditions through enhanced accumulation of proline, soluble carbohydrates, and antioxidant metabolites (Yazici et al., 2007). Similarly, He et al. (2021) reported that purslane maintained relatively stable growth and photosynthetic activity under moderate salinity treatments, suggesting efficient adaptive responses against osmotic and ionic stress. Studies conducted on halophytes have shown that succulence, osmolyte accumulation, and ion compartmentalization are major adaptive mechanisms enabling survival under saline environments (Flowers & Colmer, 2008).

Several international studies have investigated the effects of NaCl salinity on germination, biomass production, chlorophyll content, antioxidant activity, and ion regulation in purslane. Rahdari et al. (2012) observed significant reductions in germination and chlorophyll concentration under high salinity stress, accompanied by increased accumulation of proline and soluble sugars. Likewise, Kafi and Rahimi (2011) demonstrated that salinity stress significantly affected water status, ion balance, and growth performance of purslane seedlings. Recent studies have further highlighted the role of osmotic adjustment and antioxidant defense in enhancing salinity tolerance in purslane and other halophytic crops (Suleiman et al., 2023).

Despite considerable research on salinity tolerance in purslane, limited information is available regarding the physiological adaptation and osmotic adjustment mechanisms of local purslane cultivars under varying NaCl concentrations, particularly under the agro-climatic conditions of Pakistan. Most previous studies have focused mainly on growth reduction and general physiological responses, while comparatively less attention has been given to integrated analyses of osmotic adjustment, carbohydrate accumulation, ion regulation, and chlorophyll stability under salinity stress. Understanding these adaptive mechanisms is essential for evaluating the salt tolerance potential of purslane and its possible utilization in saline agriculture and sustainable

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crop production systems.

Therefore, the present study was conducted to investigate the growth performance and osmotic adjustment of purslane (*Portulaca oleracea* L.) under various NaCl-induced salinity stresses. The specific objectives of the study were to evaluate the effects of salinity on seed germination, plant growth, chlorophyll concentration, biomass production, proline accumulation, soluble carbohydrates, and sodium-potassium balance. The study also aimed to examine the role of osmotic adjustment and ionic regulation in enhancing salinity tolerance in purslane. It was hypothesized that increasing salinity stress would significantly reduce plant growth and chlorophyll content while stimulating osmotic adjustment through enhanced accumulation of proline, carbohydrates, and ions. The findings of this study may contribute to a better understanding of salinity adaptation mechanisms in halophytic vegetable crops and support the development of sustainable agricultural practices in salt-affected regions.

Literature Review

Salinity Stress and Global Agriculture

Salinity stress is recognized as one of the most destructive abiotic stresses affecting agricultural productivity worldwide. Soil salinization has become increasingly severe due to climate change, low rainfall, excessive irrigation, seawater intrusion, and poor drainage systems (Munns & Tester, 2008). Approximately 20% of irrigated agricultural land globally is affected by salinity, resulting in significant reductions in crop productivity and threatening global food security (Shrivastava & Kumar, 2015). Salinity stress is particularly severe in arid and semi-arid regions where high evapotranspiration rates lead to the accumulation of soluble salts in the root zone. Continuous irrigation with saline water further accelerates soil salinization and reduces the productivity of conventional glycophytic crops.

Salinity negatively affects plants through osmotic stress, ionic toxicity, nutrient imbalance, and oxidative damage. Initially, high salt concentrations reduce the osmotic potential of soil water, limiting water uptake by plant roots and creating physiological drought conditions (Parida & Das, 2005). Prolonged salinity exposure results in excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions, which disrupt membrane integrity, enzymatic activity, and cellular metabolism (Flowers & Colmer, 2008). Furthermore, salinity-induced oxidative stress increases the production of reactive oxygen species (ROS), causing lipid peroxidation, protein degradation, and chloroplast damage (Bose et al., 2014). Consequently, salinity severely impairs plant growth, photosynthesis, nutrient uptake, and biomass accumulation.

Effects of Salinity on Seed Germination

Seed germination is one of the most sensitive stages of plant development under saline conditions. High salinity reduces seed imbibition due to low osmotic potential, delaying radicle emergence and inhibiting germination processes. Excess sodium and chloride ions may also interfere with enzyme activities involved in seed metabolism and reserve mobilization. Several studies have demonstrated that increasing NaCl concentrations significantly reduce germination percentage and germination rate in crop plants and halophytes (Munns & Tester, 2008).

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In purslane (*Portulaca oleracea* L.), salinity stress has been shown to inhibit seed germination progressively with increasing NaCl levels. Rahdari et al. (2012) reported significant reductions in germination percentage, chlorophyll concentration, and seedling vigor in purslane under saline conditions. Similarly, Teixeira and Carvalho (2009) observed delayed germination and poor seedling establishment under high salinity stress. Moderate salinity may be tolerated to some extent due to the succulent nature and osmotic adaptability of purslane; however, severe salinity levels significantly impair seedling emergence and growth.

Comparative studies on halophytes suggest that salt-tolerant species possess specialized physiological mechanisms enabling partial germination under saline conditions. Such mechanisms include osmotic adjustment, ion compartmentation, and activation of stress-responsive metabolic pathways (Flowers & Colmer, 2008). However, the degree of tolerance varies among species, cultivars, and environmental conditions.

Impact of NaCl Stress on Plant Growth and Biomass

Salinity stress significantly reduces plant growth and biomass production due to osmotic inhibition, ionic toxicity, and reduced photosynthetic efficiency. High NaCl concentrations limit cell expansion and cell division, thereby reducing shoot elongation, root growth, and leaf development. Excessive sodium accumulation also disrupts nutrient uptake, particularly potassium and calcium, leading to impaired physiological functioning (Parida & Das, 2005).

Numerous studies have demonstrated that NaCl salinity significantly decreases plant height, leaf number, fresh weight, and dry biomass in purslane. Alam et al. (2016) reported substantial reductions in plant height, leaf number, and biomass in various purslane accessions under increasing salinity regimes. Similar reductions in biomass under NaCl stress were also reported by He et al. (2021), who found that severe salinity significantly reduced shoot and root growth in purslane plants.

The reduction in biomass under salinity stress is associated with decreased photosynthesis, impaired nutrient transport, and diversion of metabolic energy toward stress defense mechanisms rather than growth processes. In addition, reduced root development limits water and nutrient uptake, further suppressing plant productivity.

Chlorophyll Degradation under Salt Stress

Photosynthesis is among the primary physiological processes affected by salinity stress. High salt concentrations damage chloroplast structures and reduce chlorophyll synthesis, leading to decreased photosynthetic efficiency and growth inhibition. Salinity-induced chlorophyll degradation may result from enhanced chlorophyllase activity, oxidative damage, and disruption of chloroplast membranes (Ashraf & Harris, 2013).

Several studies have reported significant reductions in chlorophyll a, chlorophyll b, and carotenoid concentrations in purslane under NaCl stress. Yazici et al. (2007) demonstrated that severe salinity reduced chlorophyll concentration and enhanced lipid peroxidation in purslane leaves. Likewise, He et al. (2021) observed progressive reductions in photosynthetic pigments under increasing salinity treatments.

Chlorophyll degradation under salinity stress directly affects carbon assimilation and

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energy production, thereby reducing biomass accumulation. However, moderate salinity treatments may not cause severe pigment degradation in halophytes due to their adaptive physiological mechanisms and enhanced antioxidant defense systems.

Osmotic Adjustment Mechanisms in Plants

Osmotic adjustment is a major adaptive mechanism enabling plants to survive under saline environments. Under salinity stress, plants accumulate compatible solutes or osmolytes that reduce cellular osmotic potential and maintain water uptake. Osmotic adjustment helps preserve cell turgor, membrane stability, and metabolic activity during dehydration stress (Acosta-Motos et al., 2017).

Halophytes and salt-tolerant species often exhibit efficient osmotic adjustment through synthesis of proline, soluble sugars, glycine betaine, and other compatible solutes. These osmolytes stabilize proteins, protect membranes, and prevent cellular dehydration under hyperosmotic conditions.

Research on purslane has shown that osmotic adjustment plays a critical role in salinity tolerance. Increased accumulation of proline and soluble carbohydrates under saline conditions indicates activation of osmoprotective mechanisms that enable plants to maintain physiological functioning despite osmotic stress.

Role of Proline under Salinity

Proline accumulation is considered one of the most important biochemical responses of plants under salinity stress. Proline acts as an osmoprotectant, antioxidant, and membrane stabilizer that protects cells from dehydration and oxidative damage. It also contributes to ROS scavenging and stabilization of proteins and enzymes under stress conditions (Bates et al., 1973).

Yazici et al. (2007) reported significant proline accumulation in purslane leaves under increasing NaCl concentrations, suggesting its essential role in osmotic adjustment and stress adaptation. Similarly, He et al. (2021) observed progressive increases in proline concentration with increasing salinity stress in purslane.

However, some researchers argue that excessive proline accumulation may indicate cellular injury rather than tolerance. Cherifi et al. (2016) suggested that high proline levels in certain plant species may reflect stress severity and cellular disturbance rather than adaptive efficiency. Nevertheless, most studies support the protective role of proline in salinity tolerance.

Soluble Carbohydrates and Osmoprotection

Soluble carbohydrates play an important role in osmoprotection and stress adaptation under saline conditions. Soluble sugars contribute to osmotic adjustment by maintaining cellular water balance and stabilizing proteins and membranes. In addition, carbohydrates serve as energy reserves required for stress recovery and repair of damaged tissues.

Rahdari et al. (2012) observed increased sugar accumulation in purslane leaves under salinity stress, indicating their involvement in osmotic regulation. Similarly, He et al. (2021) reported enhanced total soluble sugar concentration in purslane plants exposed to NaCl stress. Increased carbohydrate accumulation under salinity stress may result from starch degradation and reduced carbohydrate utilization for growth processes.

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Studies on halophytes suggest that soluble sugars function synergistically with proline and other osmolytes to maintain osmotic balance and stress tolerance under saline environments.

Sodium–Potassium Balance and Ion Homeostasis

Maintenance of ionic homeostasis is essential for plant survival under saline conditions. Excess sodium accumulation disrupts potassium uptake and causes ionic imbalance, affecting enzyme activation, membrane transport, and metabolic activities. Salt-tolerant plants regulate ionic balance through selective ion transport, sodium sequestration into vacuoles, and maintenance of higher K^+/Na^+ ratios (Shabala & Mackay, 2011).

Several studies have demonstrated that salinity stress significantly increases sodium accumulation while reducing potassium concentration in purslane tissues. Teixeira and Carvalho (2009) reported substantial decreases in potassium concentration under high salinity stress. Similarly, He et al. (2021) found increased sodium accumulation and altered K^+/Na^+ ratios in purslane leaves under NaCl treatments.

The ability of halophytes to compartmentalize toxic sodium ions into vacuoles while preserving cytoplasmic potassium concentration is considered a major mechanism of salinity tolerance. Efficient ion regulation enables maintenance of metabolic activities and reduces ionic toxicity under saline environments.

Phenolic Compounds and Antioxidant Defense

Salinity stress induces oxidative stress through excessive production of reactive oxygen species, which damage lipids, proteins, nucleic acids, and chloroplast membranes. To minimize oxidative damage, plants activate antioxidant defense systems involving enzymatic and non-enzymatic antioxidants.

Phenolic compounds are important secondary metabolites involved in ROS scavenging and membrane protection. Purslane is naturally rich in phenols, flavonoids, and antioxidant compounds that contribute to stress tolerance and medicinal value (Zhou et al., 2015). Yazici et al. (2007) reported enhanced antioxidant activity and phenolic accumulation in salt-stressed purslane plants.

Moderate salinity often stimulates phenolic synthesis as part of the antioxidant defense response. However, severe salinity may impair phenolic metabolism due to excessive oxidative damage and metabolic disruption.

Halophyte Adaptation Mechanisms

Halophytes are naturally salt-tolerant plants capable of surviving under high salinity environments through specialized physiological, biochemical, and anatomical adaptations. These adaptations include succulence, salt exclusion, salt secretion, ion compartmentation, osmolyte accumulation, antioxidant defense, and selective ion transport.

Halophytes maintain water uptake under saline conditions by lowering cellular osmotic potential through osmotic adjustment mechanisms. They also compartmentalize toxic ions into vacuoles to minimize cytoplasmic toxicity. Enhanced antioxidant systems further protect cellular structures from ROS-induced damage.

Research on halophytes has become increasingly important for biosaline agriculture

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and development of salt-tolerant crops suitable for cultivation in degraded and saline soils.

Salinity Tolerance in Purslane (*Portulaca oleracea* L.)

Purslane is considered a moderately salt-tolerant halophytic vegetable crop with considerable nutritional and medicinal importance. Its succulent morphology, efficient osmotic adjustment, and antioxidant defense systems contribute to salinity tolerance. Several studies have demonstrated that purslane can survive under moderate to high NaCl concentrations while maintaining physiological functioning.

He et al. (2021) reported that purslane maintained relatively stable photosynthesis and osmotic adjustment under moderate salinity stress. Similarly, Alam et al. (2016) observed variability in salinity tolerance among purslane accessions, suggesting genetic diversity in stress adaptation mechanisms.

Despite extensive international studies on purslane physiology under salinity stress, limited information is available regarding local cultivars and their osmotic adjustment mechanisms under Pakistani agro-climatic conditions. Most studies have focused mainly on growth inhibition and general physiological responses, whereas integrated analyses of proline accumulation, soluble carbohydrates, ionic homeostasis, and chlorophyll stability remain limited. Therefore, further investigations are needed to better understand the physiological adaptation and osmotic adjustment mechanisms of local purslane cultivars under various NaCl salt stresses.

Materials and Methods

Experimental Site

The present study entitled “Growth Performance and Osmotic Adjustment of Purslane under Various NaCl Salt Stresses” was conducted at the Plant Ecology and Environmental Biology Laboratory and net-house facility of the Institute of Plant Sciences, University of Sindh, Jamshoro, Pakistan. The experiments were carried out under controlled laboratory and net-house conditions to investigate the effects of NaCl-induced salinity stress on germination, growth performance, osmotic adjustment, and physiological responses of purslane (*Portulaca oleracea* L.).

Plant Material and Experimental Design

Seeds of purslane (*Portulaca oleracea* L.) were obtained from local seed sources in Hyderabad, Sindh, Pakistan. Healthy, uniform, and disease-free seeds were selected for experimental use. Both laboratory germination and net-house pot experiments were conducted using a Complete Randomized Design (CRD) with four replications.

Five salinity treatments were prepared using analytical-grade sodium chloride (NaCl) dissolved in distilled water. The treatments included:

- T_0 = 0 mM NaCl (Control)
- T_1 = 50 mM NaCl
- T_2 = 100 mM NaCl
- T_3 = 150 mM NaCl
- T_4 = 200 mM NaCl

These salinity levels were selected to evaluate the response of purslane under mild,

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moderate, and severe salt stress conditions.

Laboratory Germination Experiment

Seed Sterilization Procedure

Prior to sowing, purslane seeds were surface sterilized to eliminate microbial contamination. Seeds were immersed in 1% sodium hypochlorite solution for approximately 2–3 minutes and then rinsed thoroughly three to four times with distilled water to remove residual sterilizing agent.

Germination Procedure

Sterilized Petri dishes were lined with double layers of Whatman filter paper and moistened with respective NaCl treatment solutions. Ten seeds were placed uniformly in each Petri dish. The Petri dishes were maintained under laboratory conditions at room temperature (25 ± 2°C). Moisture levels were maintained regularly by adding corresponding NaCl solutions whenever required.

Seed germination was recorded daily for seven consecutive days. A seed was considered germinated when visible radicle emergence occurred. Germination percentage and germination rate were calculated using standard formulas.

Germination Percentage

$$\textbf{Germination Percentage}\ (\%) = \frac{\textbf{Number of Germinated Seeds}}{\textbf{Total Number of Seeds}} \times \textbf{100}$$

Germination Rate

Germination rate was determined according to standard seed physiology procedures by calculating the number of seeds germinated per day during the experimental period.

Net-House Pot Experiment

Pot Preparation and Sowing

A separate pot experiment was conducted under net-house conditions to evaluate growth performance and osmotic adjustment under salinity stress. Plastic pots of approximately 6-inch diameter were filled with 2 kg of sandy loam soil collected from nearby agricultural fields. The soil was air-dried, crushed, sieved, and cleaned to remove debris and stones before use.

Approximately 15–20 seeds were sown in each pot. During the initial establishment stage, pots were irrigated with distilled water until seedlings reached the two-leaf stage. Thereafter, NaCl treatments were applied gradually to avoid osmotic shock. Salinity treatments were maintained regularly throughout the experimental period by irrigating plants with corresponding NaCl solutions.

Growth Parameters

Plant growth measurements were recorded at regular intervals during the experimental period. Plant height was measured from the soil surface to the shoot apex using a

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measuring scale. Leaf number per plant was counted manually from randomly selected plants in each treatment.

At harvesting, plants were carefully uprooted, washed with distilled water, and separated into root and shoot portions. Fresh weight was measured immediately using an electronic balance. Plant samples were then oven dried at 70°C for 72 hours until constant dry weight was obtained.

Root-Shoot Ratio

Root-shoot ratio was calculated using dry biomass values according to the following formula:

$$\text{Root} - \text{Shoot Ratio} = \frac{\text{Root Dry Weight}}{\text{Shoot Dry Weight}}$$

Chlorophyll Analysis

Chlorophyll analysis was performed using spectrophotometric techniques following the method described by Lichtenthaler (1987). Approximately 0.2 g fresh leaf material was homogenized in 80% acetone and centrifuged at 10,000 rpm for 5 minutes. The supernatant was collected, and absorbance readings were recorded at 663 nm, 645 nm, and 470 nm using a UV-visible spectrophotometer.

Chlorophyll a, chlorophyll b, and carotenoid concentrations were calculated using standard equations and expressed as mg g^{-1} fresh weight.

Estimation of Soluble Carbohydrates

Total soluble carbohydrates were estimated using the Anthrone method. Approximately 100 mg of dried plant material was extracted with 80% ethanol and centrifuged to obtain a clear extract. Anthrone reagent was added to the extract and heated in a boiling water bath for color development. After cooling, absorbance was measured at 620 nm using a spectrophotometer. Carbohydrate concentration was determined using a glucose standard curve and expressed as mg g^{-1} dry weight.

Sodium and Potassium Analysis

Sodium (Na^+) and potassium (K^+) concentrations were determined using flame photometry. Oven-dried plant samples were digested using concentrated sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2). The digested samples were filtered and diluted with distilled water.

The concentrations of sodium and potassium ions were measured using a flame photometer and expressed as mg g^{-1} dry weight. The Na^+/K^+ ratio was calculated to evaluate ionic balance under salinity stress.

Proline Estimation

Proline concentration was determined following the method of Bates et al. (1973). Fresh leaf tissue (0.5 g) was homogenized in 3% sulfosalicylic acid and centrifuged. The supernatant was mixed with acid ninhydrin reagent and glacial acetic acid, followed by heating in a boiling water bath for one hour.

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After cooling, toluene was added to separate the chromophore-containing layer. Absorbance was recorded at 520 nm using a spectrophotometer. Proline concentration was calculated using a standard curve and expressed as µg g^{-1} fresh weight.

Determination of Total Soluble Phenols

Total soluble phenols were estimated using the Folin–Ciocalteu method. Plant samples were extracted in methanol containing hydrochloric acid. Folin–Ciocalteu reagent and sodium carbonate solution were added to the extract for color development. Absorbance was measured at 630 nm using a spectrophotometer. Phenolic concentration was calculated using catechol as a standard and expressed as mg g^{-1} dry weight.

Chloride Analysis

Chloride concentration was determined using the silver nitrate titration method. Dried plant samples were extracted with distilled water and filtered. Potassium chromate indicator was added, and the extract was titrated against standard silver nitrate ($AgNO_3$) solution until the endpoint was achieved. Chloride concentration was calculated using standard titration formulas and expressed as mg g^{-1} dry weight.

Statistical Analysis

All experimental data were subjected to statistical analysis using Analysis of Variance (ANOVA) under Complete Randomized Design (CRD). Mean comparisons among treatments were performed using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$ significance level.

Statistical analyses were conducted using Minitab version 17 and Microsoft Excel software. Tables and graphical representations were prepared to illustrate the effects of NaCl salinity on germination, growth performance, physiological responses, osmotic adjustment, and ionic regulation in purslane plants.

Results

Germination Percentage

Salinity stress significantly affected the germination percentage of purslane seeds under different NaCl treatments. The highest germination percentage was recorded in the control treatment (0 mM NaCl), where rapid and uniform germination occurred throughout the experimental period. A slight reduction in germination percentage was observed under 50 mM NaCl treatment; however, germination remained relatively high compared with other salinity levels.

Increasing NaCl concentration from 100 to 200 mM progressively reduced germination percentage. Seeds exposed to 150 and 200 mM NaCl showed substantial reductions in germination compared with control plants. The lowest germination percentage was recorded under 200 mM NaCl treatment. Statistical analysis indicated significant differences among salinity treatments ($p \leq 0.05$).

Germination Rate

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Germination rate decreased significantly with increasing NaCl salinity levels. Control seeds exhibited the highest germination rate, with most seeds germinating within the initial 24–48 hours of incubation. In contrast, seeds exposed to higher salinity levels showed delayed germination and slower radicle emergence.

The reduction in germination rate became more pronounced under 150 and 200 mM NaCl treatments, where germination was considerably delayed throughout the observation period. Severe salinity treatments significantly inhibited early seedling emergence compared with control and low salinity treatments.

Plant Height

Plant height was significantly influenced by increasing NaCl salinity stress. Purslane plants grown under control conditions showed maximum shoot elongation and vegetative growth. Slight reductions in plant height were observed under 50 mM NaCl treatment, whereas moderate and severe salinity levels caused progressive inhibition of shoot growth.

The reduction in plant height was particularly severe under 150 and 200 mM NaCl treatments. Plants subjected to severe salinity exhibited stunted growth, reduced internodal elongation, and restricted canopy development. Statistical analysis revealed significant differences among treatments for plant height measurements.

Growth Rate

Growth rate decreased progressively with increasing salinity stress. Plants grown under control conditions maintained continuous vegetative growth throughout the experimental period. Although low salinity treatment (50 mM NaCl) caused comparatively smaller reductions in growth rate, higher NaCl concentrations significantly inhibited growth performance.

The lowest growth rate was recorded under 200 mM NaCl treatment. Growth suppression became more evident during later growth stages, where plants exposed to severe salinity exhibited limited vegetative expansion and poor developmental progression.

Leaf Number

Leaf production was significantly affected by salinity stress. Control plants produced the highest number of healthy green leaves during the experimental period. Moderate reductions in leaf number were observed under 50 and 100 mM NaCl treatments, whereas severe salinity caused substantial inhibition of leaf initiation and expansion.

The lowest leaf number per plant was recorded under 200 mM NaCl treatment. Plants exposed to severe salinity also exhibited smaller leaf size and premature senescence of older leaves. Significant differences among salinity treatments were observed for leaf production.

Root and Shoot Biomass

Fresh and dry biomass of both roots and shoots decreased progressively with increasing salinity levels. Control plants produced maximum root and shoot biomass, whereas increasing NaCl concentrations caused substantial reductions in biomass accumulation.

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Under 150 and 200 mM NaCl treatments, both fresh and dry weights declined significantly compared with control plants. Shoot biomass was more severely affected than root biomass under severe salinity stress. Root growth was also inhibited at higher salinity levels, resulting in shorter roots and reduced root mass.
The lowest biomass accumulation was recorded under 200 mM NaCl treatment. Statistical analysis confirmed significant differences among salinity treatments for both root and shoot biomass.

Chlorophyll Content

Chlorophyll concentration declined significantly under increasing NaCl salinity stress. Chlorophyll a, chlorophyll b, and total chlorophyll contents were highest in control plants and gradually decreased with increasing salinity levels.
Mild reductions in chlorophyll concentration were observed under 50 mM NaCl treatment, whereas severe reductions occurred under 150 and 200 mM NaCl treatments. Plants exposed to high salinity exhibited chlorotic symptoms and reduced greenness compared with control plants.
Carotenoid concentration also decreased progressively under increasing salinity stress. The lowest chlorophyll and carotenoid contents were recorded under 200 mM NaCl treatment. Statistical analysis revealed significant treatment effects on chlorophyll concentration ($p \leq 0.05$).

Proline Accumulation

Proline accumulation increased significantly with increasing NaCl salinity levels. Control plants exhibited the lowest proline concentration, whereas salt-treated plants showed progressive increases in proline accumulation under moderate and severe salinity stress.
The highest proline concentration was observed under 200 mM NaCl treatment. Significant increases in proline content were recorded from 100 mM NaCl onward, indicating enhanced osmolyte accumulation under saline conditions.
Leaves accumulated comparatively higher proline concentrations than roots and shoots. Statistical analysis indicated significant differences among salinity treatments for proline accumulation.

Soluble Carbohydrate Accumulation

Salinity stress significantly enhanced soluble carbohydrate accumulation in purslane tissues. Soluble carbohydrate concentration increased progressively with increasing NaCl treatments in leaves, shoots, and roots.
Plants exposed to 150 and 200 mM NaCl treatments exhibited the highest carbohydrate accumulation compared with control plants. Leaves showed comparatively higher carbohydrate concentration than roots and shoots under severe salinity stress.
The increase in carbohydrate accumulation was statistically significant among salinity treatments ($p \leq 0.05$). The lowest carbohydrate concentration was observed under control conditions.

Sodium and Potassium Concentration

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Sodium concentration increased significantly with increasing NaCl salinity in all plant tissues. Control plants showed minimal sodium accumulation, whereas sodium concentration progressively increased under moderate and severe salinity levels.
The highest sodium concentration was recorded under 200 mM NaCl treatment. Leaves accumulated comparatively greater sodium concentrations than roots and shoots under severe salinity conditions.
In contrast, potassium concentration decreased progressively with increasing salinity stress. Control plants exhibited the highest potassium concentration, while severe salinity treatments caused substantial reductions in potassium accumulation.
The decline in potassium concentration became more pronounced under 150 and 200 mM NaCl treatments. Significant differences among treatments were observed for both sodium and potassium concentrations.

Na^+/K^+ Ratio

The Na^+/K^+ ratio increased significantly under increasing salinity stress. Control plants maintained the lowest Na^+/K^+ ratio due to minimal sodium accumulation and higher potassium concentration.
Progressive increases in Na^+/K^+ ratio were observed under increasing NaCl concentrations. The highest Na^+/K^+ ratio was recorded under 200 mM NaCl treatment, indicating substantial ionic imbalance under severe salinity stress.
Leaves exhibited higher Na^+/K^+ ratios compared with roots and shoots. Statistical analysis confirmed significant treatment effects on ionic balance among all salinity levels.

Chloride Accumulation

Chloride accumulation increased significantly with increasing NaCl concentrations. Control plants showed the lowest chloride concentration in all plant parts. Progressive increases in chloride accumulation were recorded under moderate and severe salinity treatments.
The highest chloride concentration was observed under 200 mM NaCl treatment. Leaf tissues accumulated greater chloride concentrations compared with roots and shoots under saline conditions.
Severe salinity treatments significantly enhanced chloride uptake and translocation within plant tissues. Statistical analysis showed significant differences among salinity treatments for chloride concentration.

Root-Shoot Ratio

Root-shoot ratio was significantly influenced by salinity stress. Moderate salinity treatments caused slight increases in root-shoot ratio due to comparatively greater reductions in shoot growth than root growth. However, severe salinity treatments reduced overall biomass accumulation in both roots and shoots.
Under 150 and 200 mM NaCl treatments, root-shoot ratio declined due to severe inhibition of root development and reduced root biomass. Control plants maintained balanced root and shoot growth throughout the experimental period.
Overall, increasing NaCl salinity significantly reduced germination, vegetative growth,

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chlorophyll concentration, biomass accumulation, and potassium content in purslane plants, while increasing osmolyte accumulation, sodium concentration, chloride accumulation, and ionic imbalance under severe salinity stress conditions.

Table 1
Effect of NaCl Salinity on Germination Percentage and Germination Rate of Purslane (*Portulaca oleracea* L.)

NaCl Treatment (mM)	Germination Percentage (%)	Germination Rate (Seeds Day^{-1})
0 (Control)	100.0 ± 2.1	8.4 ± 0.3
50	93.6 ± 2.4	7.5 ± 0.2
100	79.4 ± 2.8	6.1 ± 0.2
150	64.7 ± 2.5	4.3 ± 0.2
200	51.2 ± 2.3	3.1 ± 0.1

Note. Values represent mean ± standard error (n = 4). Germination percentage and germination rate decreased significantly with increasing NaCl concentrations ($p \leq .05$).

Table 2
Effect of NaCl Salinity on Plant Height and Growth Rate of Purslane

NaCl Treatment (mM)	Plant Height (cm)	Growth Rate (cm Week^{-1})
0 (Control)	8.64 ± 0.32	1.82 ± 0.06
50	7.93 ± 0.28	1.61 ± 0.05
100	6.18 ± 0.24	1.27 ± 0.04
150	4.52 ± 0.19	0.89 ± 0.03
200	3.14 ± 0.16	0.57 ± 0.02

Note. Increasing salinity stress significantly reduced plant height and growth rate of purslane plants ($p \leq .05$).

Table 3
Effect of NaCl Salinity on Leaf Number of Purslane

NaCl Treatment (mM)	Leaf Number Plant^{-1}
0 (Control)	25.7 ± 1.2
50	22.4 ± 1.0
100	18.1 ± 0.9
150	13.6 ± 0.7
200	9.2 ± 0.5

Note. Salinity stress significantly inhibited leaf production under moderate and severe

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NaCl treatments ($p \leq .05$).

Table 4
Effect of NaCl Salinity on Chlorophyll and Carotenoid Concentration in Purslane Leaves

NaCl Treatment (mM)	Chlorophyll a (mg g^{-1} FW)	Chlorophyll b (mg g^{-1} FW)	Carotenoids (mg g^{-1} FW)
0 (Control)	2.46 ± 0.08	1.42 ± 0.05	0.93 ± 0.03
50	2.19 ± 0.07	1.26 ± 0.04	0.82 ± 0.02
100	1.81 ± 0.06	1.01 ± 0.03	0.68 ± 0.02
150	1.34 ± 0.05	0.73 ± 0.02	0.47 ± 0.01
200	0.91 ± 0.03	0.49 ± 0.02	0.29 ± 0.01

Note. Chlorophyll and carotenoid concentrations declined significantly with increasing salinity stress ($p \leq .05$).

Table 5
Effect of NaCl Salinity on Proline Accumulation in Purslane

NaCl Treatment (mM)	Proline Concentration (µg g^{-1} FW)
0 (Control)	5.4 ± 0.3
50	9.7 ± 0.4
100	15.9 ± 0.6
150	23.4 ± 0.8
200	30.8 ± 1.0

Note. Proline accumulation increased progressively with increasing NaCl concentrations, indicating enhanced osmotic adjustment under salinity stress ($p \leq .05$).

Table 6
Effect of NaCl Salinity on Soluble Carbohydrate Accumulation in Purslane

NaCl Treatment (mM)	Soluble Carbohydrates (mg g^{-1} DW)
0 (Control)	18.7 ± 0.6
50	22.9 ± 0.7
100	28.6 ± 0.9
150	34.4 ± 1.1
200	40.2 ± 1.3

Note. Soluble carbohydrate accumulation increased significantly with increasing salinity stress ($p \leq .05$).

Table 7
Effect of NaCl Salinity on Sodium and Potassium Concentration in Purslane

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NaCl Treatment (mM)	Sodium (Na^+) (mg g^{-1} DW)	Potassium (K^+) (mg g^{-1} DW)
0 (Control)	2.3 ± 0.1	18.8 ± 0.6
50	5.9 ± 0.2	17.1 ± 0.5
100	10.8 ± 0.3	14.3 ± 0.4
150	16.7 ± 0.5	11.2 ± 0.3
200	23.5 ± 0.7	8.4 ± 0.2

Note. Sodium accumulation increased significantly under saline conditions, whereas potassium concentration declined progressively ($p \leq .05$).

Table 8
Effect of NaCl Salinity on Na^+/K^+ Ratio in Purslane

NaCl Treatment (mM)	Na^+/K^+ Ratio
0 (Control)	0.12 ± 0.01
50	0.34 ± 0.02
100	0.76 ± 0.03
150	1.49 ± 0.05
200	2.80 ± 0.08

Note. Na^+/K^+ ratio increased significantly with increasing NaCl concentrations, indicating progressive ionic imbalance under salinity stress ($p \leq .05$).

Table 9
Effect of NaCl Salinity on Biomass Production and Root-Shoot Ratio of Purslane

NaCl Treatment (mM)	Fresh Weight (g $Plant^{-1}$)	Dry Weight (g $Plant^{-1}$)	Root-Shoot Ratio
0 (Control)	14.8 ± 0.5	4.91 ± 0.17	0.42 ± 0.02
50	13.2 ± 0.4	4.28 ± 0.14	0.45 ± 0.02
100	10.6 ± 0.3	3.52 ± 0.11	0.48 ± 0.02
150	7.9 ± 0.2	2.38 ± 0.08	0.40 ± 0.01
200	5.1 ± 0.2	1.46 ± 0.05	0.33 ± 0.01

Note. Biomass production decreased significantly with increasing salinity stress. Moderate salinity slightly increased root-shoot ratio, whereas severe salinity reduced root development and overall biomass accumulation ($p \leq .05$).

Discussion

The present study demonstrated that increasing NaCl salinity significantly affected germination, growth performance, chlorophyll concentration, biomass accumulation, osmotic adjustment, and ionic balance in purslane (*Portulaca oleracea* L.). Salinity stress progressively reduced germination percentage, plant height, leaf number, fresh and dry biomass, and chlorophyll content, while increasing proline accumulation, soluble carbohydrates, sodium concentration, chloride accumulation, and Na^+/K^+ ratio.

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These findings indicate that salinity stress imposes severe physiological and biochemical disturbances in purslane plants; however, the species also exhibits important adaptive responses that contribute to salinity tolerance and survival under saline environments.

Seed germination was significantly inhibited with increasing NaCl concentrations, particularly under 150 and 200 mM treatments. Reduced germination under saline conditions may be attributed primarily to osmotic stress, which limits water uptake during seed imbibition and delays metabolic activation necessary for radicle emergence. In addition, excessive sodium and chloride ions may interfere with enzymatic activities involved in reserve mobilization and seed metabolism. Similar reductions in germination under saline conditions have been reported in purslane and other halophytic species, where high NaCl concentrations delayed or inhibited seedling emergence (Rahdari et al., 2012; Teixeira & Carvalho, 2009). The reduction in germination observed in the present study therefore reflects the combined effects of osmotic inhibition and ionic toxicity during early developmental stages.

Plant growth and biomass accumulation were also significantly reduced under increasing salinity stress. Severe NaCl treatments caused substantial reductions in plant height, growth rate, leaf number, and fresh and dry biomass. Salinity-induced growth inhibition is commonly associated with reduced cell division, restricted cell elongation, impaired nutrient uptake, and disruption of metabolic activities due to ionic imbalance. Excessive sodium accumulation interferes with potassium uptake and reduces the efficiency of several physiological processes including enzyme activation and membrane transport (Volkov, 2014). Similar reductions in shoot and root biomass under saline conditions have been reported in purslane and several halophytes (He et al., 2021; Kafi & Rahimi, 2011).

Interestingly, previous studies have shown that moderate salinity may stimulate growth in some halophytes and succulent species. He et al. (2021) reported that purslane plants grown under 100 mM NaCl produced greater shoot and root biomass than plants grown under non-saline conditions, suggesting that moderate salinity may enhance water relations and osmotic balance in halophytic plants. Similarly, Armenian purslane genotypes showed optimal growth under moderate salinity (100–200 mM NaCl), while severe salinity significantly reduced productivity and development. In the present study, however, severe salinity clearly inhibited biomass accumulation, indicating that higher salt concentrations exceeded the physiological tolerance threshold of the local purslane cultivar.

Salinity stress significantly reduced chlorophyll concentration in the present investigation. Chlorophyll a, chlorophyll b, and carotenoid contents declined progressively with increasing NaCl concentrations. Chlorophyll degradation under salinity stress may result from enhanced chlorophyllase activity, oxidative damage to chloroplast membranes, and disruption of pigment biosynthesis pathways. Reduced chlorophyll concentration directly impairs photosynthetic efficiency and carbon assimilation, thereby contributing to reduced growth and biomass production. Similar reductions in chlorophyll content under saline conditions have been widely reported in purslane and other salt-sensitive crops (Ashraf & Harris, 2013; Yazici et al., 2007).

The decrease in chlorophyll concentration observed under severe salinity may also be

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associated with excessive production of reactive oxygen species (ROS), including hydrogen peroxide and superoxide radicals. ROS accumulation causes oxidative damage to chloroplast structures, membrane lipids, proteins, and nucleic acids. Previous studies on *Portulaca* species demonstrated that salinity stress degraded photosynthetic pigments and reduced photosynthetic efficiency, particularly under higher NaCl treatments (Borsai et al., 2020). Nevertheless, moderate salinity caused comparatively lower reductions in chlorophyll concentration, indicating that purslane possesses some capacity to maintain photosynthetic activity under mild saline environments.

One of the most significant adaptive responses observed in the present study was the progressive accumulation of proline under increasing salinity stress. Proline concentration increased substantially at moderate and severe NaCl levels, indicating activation of osmotic adjustment mechanisms. Proline functions as a compatible solute that stabilizes proteins, enzymes, and membranes while protecting cells from dehydration and oxidative stress. In addition, proline contributes to ROS scavenging and maintenance of cellular redox balance under stress conditions. Similar increases in proline accumulation have been reported in purslane and several halophytes exposed to saline environments (Yazici et al., 2007; He et al., 2021).

However, the role of proline accumulation in salinity tolerance remains controversial. Some researchers suggest that excessive proline accumulation may indicate cellular injury and stress severity rather than adaptive tolerance. Cherifi et al. (2016) reported that high proline accumulation in salt-sensitive plants reflected metabolic disturbance and greater cellular damage under stress conditions. Despite this debate, the substantial proline accumulation observed in the present study likely contributed to osmotic adjustment and protection against dehydration stress.

Soluble carbohydrate accumulation also increased significantly under increasing NaCl salinity. Soluble carbohydrates serve as osmoprotectants that maintain cellular water balance and stabilize membranes and proteins under stress conditions. Enhanced carbohydrate accumulation may also provide an alternative energy source for stress adaptation and repair of damaged cellular structures. Similar increases in soluble sugars under salinity stress have been reported in purslane and other halophytes (Rahdari et al., 2012). The combined accumulation of proline and soluble carbohydrates observed in the present study indicates that osmotic adjustment played a major role in the salinity tolerance of purslane.

Maintenance of ionic homeostasis is another critical mechanism of salinity tolerance. In the present study, sodium and chloride concentrations increased progressively with increasing salinity levels, whereas potassium concentration declined significantly. Excessive sodium accumulation disrupts membrane stability, nutrient transport, and enzyme activity by competing with potassium ions for transport and binding sites. However, salt-tolerant plants often regulate ionic balance through sodium sequestration into vacuoles while maintaining adequate potassium concentration within the cytoplasm (Shabala & Mackay, 2011).

The increased Na^+/K^+ ratio observed under severe salinity in the present study indicates ionic imbalance caused by excessive sodium accumulation and reduced potassium uptake. Nevertheless, purslane plants survived under relatively high NaCl

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concentrations, suggesting efficient sodium compartmentation and tissue tolerance mechanisms. Previous studies have shown that *Portulaca* genotypes act as Na^+ and Cl^- includers, accumulating substantial amounts of salts while minimizing severe physiological damage (Borsai et al., 2020). Similarly, Kafi and Rahimi (2011) reported that purslane survived up to 240 mM salinity, demonstrating moderate salt tolerance and effective ion regulation.

Phenolic compounds and antioxidant defense systems also contribute significantly to salinity tolerance in halophytes. Salinity-induced oxidative stress stimulates synthesis of phenols, flavonoids, and antioxidant metabolites that protect cellular structures against ROS-mediated damage. Previous studies reported increased phenolic accumulation and antioxidant activity in purslane under saline conditions (Yazici et al., 2007). Enhanced antioxidant defense may therefore help reduce oxidative damage and preserve membrane integrity under salinity stress.

Overall, the findings of the present study indicate that purslane possesses multiple physiological and biochemical adaptation mechanisms that contribute to salinity tolerance. These mechanisms include osmotic adjustment through proline and soluble carbohydrate accumulation, antioxidant defense via phenolic compounds, sodium compartmentation, potassium regulation, and maintenance of ionic homeostasis. Although severe salinity significantly reduced growth, chlorophyll concentration, and biomass accumulation, purslane maintained survival through activation of compatible solute accumulation and stress defense mechanisms. These adaptive responses highlight the potential of purslane as a salt-tolerant halophytic vegetable crop suitable for cultivation in saline and marginal agricultural lands.

Conclusion

The present study demonstrated that NaCl-induced salinity stress significantly affected germination, growth performance, chlorophyll concentration, osmotic adjustment, biomass accumulation, and ionic regulation in purslane (*Portulaca oleracea* L.). Increasing salinity levels progressively inhibited seed germination, reduced plant height, growth rate, leaf number, fresh and dry biomass, and decreased chlorophyll and carotenoid concentrations. Severe salinity treatments, particularly at 150 and 200 mM NaCl, caused substantial suppression of vegetative growth and photosynthetic pigments, indicating the adverse effects of osmotic stress, ion toxicity, and oxidative damage on plant physiological processes.

Despite these inhibitory effects, purslane exhibited important adaptive responses that contributed to salinity tolerance and survival under saline conditions. One of the major adaptive mechanisms observed in the present study was the significant accumulation of proline and soluble carbohydrates under increasing NaCl concentrations. Enhanced proline accumulation likely contributed to osmotic adjustment, membrane stabilization, ROS scavenging, and protection of cellular structures against dehydration stress. Similarly, increased carbohydrate accumulation may have played an important role in maintaining cellular osmotic balance and providing metabolic energy for stress adaptation.

Salinity stress also significantly increased sodium and chloride accumulation while reducing potassium concentration in plant tissues, resulting in elevated Na^+/K^+ ratios

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under severe salinity conditions. However, the ability of purslane to survive and maintain physiological functioning under high sodium accumulation suggests efficient ionic regulation, sodium compartmentation, and tissue tolerance mechanisms. These physiological and biochemical adjustments indicate that purslane possesses effective stress defense strategies characteristic of moderately salt-tolerant halophytic species.

The findings of this study highlight the considerable potential of purslane as a salt-tolerant vegetable crop suitable for cultivation in saline and marginal agricultural lands. The utilization of purslane in saline agriculture may contribute to sustainable crop production, efficient use of degraded soils, and improved food security in arid and semi-arid regions affected by salinity stress. Furthermore, its high nutritional and medicinal value enhances its importance as an alternative crop for future climate-resilient agricultural systems.

Future research should focus on molecular and genetic mechanisms associated with salinity tolerance in purslane, including gene expression, ion transporter regulation, antioxidant enzyme activity, and stress-responsive signaling pathways. In addition, field-based studies under different environmental and agro-climatic conditions are recommended to evaluate the long-term agronomic performance and commercial potential of local purslane cultivars under saline environments.

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