ASSESSMENT OF FLOWERING ANNUALS FOR ADAPTATION TO SODIC SOILS

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(Received 14th Sep 2024; accepted 16th Jan 2025)

Abstract. To assess the suitability of flowering annuals based on their tolerance to sodicity, marigold (*Tagetes erecta* L.), cockscomb (*Celosia cristata* L.), globe amaranth (*Gomphrena globosa* L.), and amaranthus (*Amaranthus dubius* Mart. ex Thell.) were selected. Soil with an ESP of 40 was collected from Tiruchirapalli, and treated with25%, 50%, and 100% gypsum requirement to vary the ESP levels from 16 to 32. The flowering annuals were sown in the potted soils with ESP varying from 16 to 32. The findings indicated that *Gomphrena globosa* and *Celosia cristata* exhibited superior growth traits, including plant height, dry matter production, and antioxidant activity, as well as favorable Na/K ratios, these traits were observed up to an ESP level of 24 compared to other flowering annuals. The result indicated that the *Gomphrena globosa* and *Celosia cristata* were highly suited to sodic soils up to 24% ESP without any amendment.
Keywords: *flowering annuals, Celosia cristata, Gomphrena globosa, Tagetes erecta, Amaranthus dubius*

Introduction

In an ecosystem, abiotic components are vital for survival andgrowth of organisms. In agrosystems as well, when these components fall below or exceed their optimum levels, they become stressors (Choudhury and Moulick, 2022), and reduces crop production by more than 50% compared to non-limiting growth environments (Dowla et al., 2021). The most common abiotic stressors-salinity, exchangeable sodium, heavy metals, floods, drought, high ozone levels, nutrient deficiency, and temperature extremes-pose serious challenges to achieving sustainable agriculture(Moulick et al., 2024).

At present, about 20 percent of the world’s irrigated land is salt-affected, and 60 percent of salt-affected soils are sodic (Negaczet al., 2022). In India, sodic soils occupy about 3.788 million hectares (Sharma et al., 2007). Sodic soils, characterized by high levels of exchangeable sodium ions, cause soil particles to disperse. This results in poor aggregation, crusting, reduced water infiltration, water logging, salt accumulation, and increased erosion risk (Sheldon et al., 2017). High sodium levels lead to deficiencies and nutrient imbalance, resulting in reduced crop yield and even death (Shahid et al.,2018)without a doubt (Litalien and Zeeb, 2020). Salinization and sodification of soils endanger environmental sustainability and agricultural crop productivity (Ivushkin et al., 2019). Soil salinization and sodification processes mostly characterize dryland regions (Cuevas et al., 2019). Yet climatic changes, with forecasted increasing temperatures and growing frequency and magnitude of droughts in moisture climatic regions, alongside the aggravated drying and expansion of the world’s dry lands (Huang et al., 2017), make soil salinization and sodification, a global challenge.

Over time, the extent of sodic croplands has increased, resulting in accelerated land degradation and desertification, decreased agricultural productivity, and consequently jeopardizing environmental and food security. Sodic soils are indeed considered wastelands in agricultural terms due to their adverse effects, further exacerbating the issue of land degradation and desertification.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

Yield loss under sodicity varies with the extent of the increase in pH and ESP. A significant reduction of root and shoot growth and grain yield, but deterioration is known to vary with cultivar and growth stage. Crop grown under sodic soil conditions can be adversely affected by water-logging during winter due to water accumulating in the topsoil as rainfall exceeds evapotranspiration. Efforts to reclaim sodic soils typically involve amendments such as gypsum to replace sodium with calcium, improving soil structure and fertility. However, the process can be costly and time-consuming, making sodic soils challenging to rehabilitate.

The high sodium content resulted in high SAR, soil alkalinity and high pH level which necessitated suitable amendment (gypsum) and land management practices to sustain the agricultural production (Iqbal et al., 2018).Escalated price of amendments, scarcity of freshwater caused by the impacts of climate change accentuate the problem. The alternatives include advanced measures for flushing and leaching, water-saving irrigation technologies, precision fertilizer systems, application of chemical amendments, bioremediation, and phyto-remediation of affected lands. Identification of tolerant species, ion uptake mechanism and transport properties needs to be studied (Huang et al., 2020).

In response to these challenges, there is a growing need to identify plant species capable of thriving in sodic soil, thereby offering sustainable solutions for agriculture in such areas. Flowers are extensively used in the preparation of garlands and as loose flowers on the occasion of religious ceremonies, festive occasions, offerings etc. Apart from loose flowers, carotenoids extracted from flowers are used for industrial purposes (pharmaceuticals, food supplements, animal feed additives and colorants in food and cosmetics).

The productivity of sodic soils can be improved by using salt-tolerant crops and implementing appropriate agronomic practices (Singh et al., 2016).In India, marigold cultivation spans 0.26 million hectares, yielding a production of1.93 million tonnes of loose flowers. In Tamil Nadu itself the area under marigold is 0.028 million hectares. The commonly cultivated species of marigold are African marigold and French marigold (*Tagetes patula*). Marigolds are very easy to grow and grow fast. African marigold is a popular flower crop grown throughout the world on a commercial scale.

Among marigold species, the African marigold (*Tagetes erecta*) is particularly recognized for its high adaptability and resilience in challenging environments. Its robust root system significantly contributes to stress tolerance, making it an excellent candidate for phyto-remediation and biomass production etc., programmes (Farooqetal.,2020; Biswal et al., 2022; Khilji et al., 2024). Beyond its environmental advantages, cultivating marigold improves soil moisture, boosts enzyme activity, and enhances nitrogen availability. Intercropping with marigold further strengthens these benefits, improving soil properties, metabolomics, and the structure of bacterial communities (Xue et al., 2023). Additionally, African marigold exhibits an efficient sodium (Na^+) exclusion mechanism that reduces sodium uptake, mitigating ionic stress in saline soils. While salinity may hinder growth and yield, it simultaneously stimulates the production of antioxidants, enriching the plant with valuable nutritional compounds (Guzmán and Marques, 2023).

Celosia cristata, commonly known as the crested cockscomb, is a flowering plant native to India. Its striking blossoms, resembling a rooster's head, make it a popular ornamental choice. Beyond its aesthetic appeal, it is also valued as a vegetable, fodder, and for its medicinal properties. Notably, its resilience under various environmental

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
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stresses further highlights its potential in agricultural applications (Harisha, 2023). When exposed to such stresses, *C. cristata* exhibits changes in ion concentrations consistent with well-documented physiological responses (Carter et al., 2005). Research underscores its ability to tolerate a range of abiotic challenges, demonstrating adaptability that varies depending on specific conditions (Bezerra et al., 2020). With its combination of resilience and multifunctional uses, *C. cristata* emerges as a promising candidate for challenging agricultural environments.

Gomphrena is a genus in the *Amaranthaceae* family, which includes 180 genera and 2000 to 2500 species of herbs and shrubs. While native to Central America, *Gomphrena globosa* was first introduced in India. This species is highly valued for both its ornamental beauty and its ability to improve soil quality. In particular, it shows promise in phyto-remediation, especially for arsenic-contaminated soils (Signes-Pastor et al., 2015). Thanks to its robust nature, *Gomphrena globosa* can withstand a wide range of environmental conditions, making it an ideal candidate for soil rehabilitation in degraded or contaminated areas. Furthermore, its flowers contain an extract rich in betacyanin, which has demonstrated significant antioxidant potential (Roriz et al., 2020). The plant also exhibits a physiological response to stress conditions by accumulating Na^+ and Cl^- ions in both its shoots and roots. This ionic accumulation, along with increased levels of phenolics, flavonoids, and antioxidant activity, underscores its resilience and adaptability. These combined traits not only enhance its role in phytoremediation but also position *Gomphrena globosa* as a promising candidate for improving soil health and restoring contaminated environments (Haripershad et al., 2024).

In addition to *Amaranthus*, several other flowering annuals are being evaluated as promising candidates for future breeding programs aimed at improving crop resilience. *Amaranthus* is noted for its high phenotypic plasticity across multiple stressors, demonstrating adaptability to conditions such as salinity, drought, and temperature fluctuations. This adaptability, shared by other flowering annuals, makes them all strong candidates for breeding programs focused on developing crops that can thrive in climate change-affected environments. These species, with their potential for soil health improvement and stress tolerance, could play a crucial role in future agricultural practices aimed at sustainable crop production and environmental restoration.

The performance of these seasonal flowering species cultivated in sodic soil with varying pH levels is reported. Despite the limited literature on the suitability of flowering annuals for sodic soils, these species collectively demonstrate their potential not only to withstand environmental stresses but also to contribute to soil health improvement. This makes them suitable candidates for sustainable agricultural practices and environmental restoration programs. Hence, this study was proposed to address the knowledge gap.

Materials and methods

The performance of selected flowering annuals for sodicity tolerance and sensitivity was studied in Pot culture at Horticultural College and Research Institute for Women Trichy. The required quantity of naturally sodic soil was collected from the coordinates of 10°45′25.8″N 78°59′35.5″E.

To get approximately 600 kg of soil an area of 2mx2m is cleared. samples were collected from the top 0–20 cm soil layer by plowing the soil with 5 tyne cultivator by using MF 9000 planetary plus Massey Ferguson tractor followed by removal of soil by using 6 feet Gomathi rotavator manufactured by Gomathi Engineering Service,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

Kunnathur, Erode. Left out soil were lifted up to 20 cm by using a crowbar manufactured locally. Gunny bags were used to lift the Collected soils to the locally manufactured tractor trolley to the experimental site. Collected samples were air-dried under shade in the nursery complex of the horticultural college, ground to break down larger clumps using wooden mallet hammer, and then passed through a 2 mm sieve to ensure a uniform particle size.

Air Pots of ten kg capacity were filled with initial soils with an ESP of 40, collected from the institute. The gypsum requirement was calculated, and the soil was treated with 25, 50, 75, and 100 percent of this requirement. Good quality water was collected from nearby Mayanor Barrage Canal, originating from Kaveri River. Reaction (pH) and electrical conductivity (EC) of the water used for the experiment was 7.58 and, 0.25 dS m^{-1}, respectively. Ca, Mg and Na contents of the water were 50, 20, and 13 ppm, respectively. Sodium adsorption ratio (SAR) of the water used was 2.2. Leaching was conducted with collected good quality water to adjust the soil to different exchangeable sodium (ESP) levels: 16, 24, 32 and used for the experiment.

The pots are kept on 7x5 m 350 GSM rectangular pvc coated nylon blue colour sheet sheets to prevent any leachate coming to contact with native soil.

The initial characteristics of soil used for field experiments are as follows: The soil had a cation exchange capacity (CEC) of 40 c mol. (+) kg^{-1} and a pH of 10.The Electrical Conductivity was 1.94dS m^{-1} and the Organic Carbon of the soil was 0.49%.Available N, P, K content of the soil were 125, 26, 225 kg ha^{-1}, respectively. Cation capacity of the soil is 26 cmol. p^{+} kg^{-1}.The Exchangeable Ca, Mg, Na, K contents of the soil were 5.46, 2.98, 14.5, 4.51 cmol. p^{+} kg^{-1}, respectively.

The experiment was conducted in a Completely Randomized Design (CRD) with three replications. Treatment consisted of selected flowering annuals *viz.*, Marigold (*Tagetes erecta*), *Celosia cristata*, Globe Amaranthus (*Gomphrena globosa*) and Amaranthus (*Amaranthus dubius*) with varying levels of sodicity based on Soil ESP. The date of planting was 30.12.2021, and observations were recorded at 70 days after sowing. A parallel experiment was also conducted for dry matter estimation, root height and root volume estimation.

The height of the plants was measured from the soil surface to the highest point of the plant (tip of the stem) using Freemans GR519 Measurement Tape (5 m). Bent stems were straightened to ensure the plant was upright. A parallel pot culture experiment was conducted to evaluate dry matter production. All pots were maintained under identical environmental conditions throughout the study. At 70 DAS, plants were carefully uprooted from the parallel pots, their roots were washed, and then dried in a digital hot air oven at 65–70°C overnight until a constant weight was obtained. The dried samples was measured using a precision balance (ATOM—MH 200).

To measure root length, the plant from the parallel experiment was carefully removed from the soil. Excess was gently washed off the roots, with care taken to avoid breaking or damaging them. The roots were laid flat on a clean surface. The longest root and any additional roots was measured using a ruler. Root volume was determined using the water displacement method. Plants were harvested from the parallel experiment with minimal damage to the root system. Excess soil was shaken off, and the roots were then placed in a graduated cylinder containing a known volume of water. Once completely submerged, the displaced water was recorded. The change in the water level corresponds directly to the root volume.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

To determine yield per pot, fully mature flowers were harvested at weekly intervals in the morning, after the pots had been irrigated a day prior. Clean, sharp scissors were used to make precise cuts, and collection trays helped prevent damage to the harvested flowers. Immediately after collection, the flowers were weighed using a calibrated scale to record their fresh weight.

To assess Vesicular-Arbuscular Mycorrhizal (VAM) propagules, soil sampling involved collecting both root-associated and non-root soil particles, as VAM propagules occur in both. Samples were gathered from varying depths and regions to ensure comprehensive representation. The collected soil was prepared by sifting through a fine 2 mm mesh to remove large debris and separate finer particles. The soil samples were then air-dried for further processing.

Soil samples were air-dried and sieved, and 1 g of soil was treated with 8 mL of 50 mM sodium citrate (pH 8.0). The mixture was then autoclaved at 121°C for 30 minutes, cooled to room temperature, and centrifuged at 4000 rpm for 20 minutes. The extraction process was repeated 2–3 times, and the supernatants were pooled. Glomalin content was assessed using the Bradford assay by mixing 0.1 mL of the pooled extract with 5 mL of Bradford reagent, followed by a 10-minute incubation. Absorbance was measured at 595 nm, and protein concentration was calculated using a Bovine Serum Albumin (BSA) standard curve. The glomalin content was finally expressed as milligrams per gram of soil. The total phenol was estimated using a colorimetric method (Spinola et al., 2018)with modifications. Specifically, 1.0 mL of varying concentrations of gallic acid, 0.2 mL of Folin-Ciocalteu reagent, and 0.6 mL of 10% (w/v) sodium carbonate were mixed with 3.2 mL of deionized water. The mixture was incubated at 30°C in the dark for 90 min, and the absorbance at 760 nm was measured using a double beam UV visible (UV–Vis) spectrophotometer model LUS-B30 manufactured by Labtron. Results were expressed as mg gallic acid equivalents per gram of freeze-dried sample (mg GAE g^{-1}) through the calibration curve of gallic acid.

The phenolic acid content was estimated using a colorimetric method (Celep et al., 2017) with modifications. Specifically, 0.5 mL of varying concentrations of caffeic acid, 3.0 mL of deionized water, 0.5 mL of 0.5 M hydrochloric acid, and 0.5 mL of Arnova reagent were mixed with 0.5 mL of 1 M sodium hydroxide. The mixture was incubated at 37°C in the dark for 10 min, and the absorbance at 490 nm was measured using double beam UV visible (UV–Vis) spectrophotometer model PLUS-B30 brand name-Labtron. Results were expressed as mg caffeic acid equivalents per gram of freeze-dried sample (mg CAE g^{-1}) through the calibration curve of caffeic acid.

Proline was extracted and estimated by standard method. A quantity of 300 mg of fresh leaves were homogenized in 10 ml of 3% aqueous sulfosalicylic acid solution using Cole-Parmer HO-400 Series Laboratory Homogenizer, and centrifuged at 9000 rpm for 15 minutes by using Avanti JXN-30 manufactured by Beckman Coulter. This procedure was repeated with the residue, and the filtrates were combined. For estimation, 2.0 ml of the filtrate was mixed with 2.0 ml of acid ninhydrin (1.25 g of ninhydrin dissolved in a warm mixture of 30 ml glacial acetic acid and 20 ml of 6 M phosphoric acid, stable for 24 hours at 4°C) and 2.0 ml of glacial acetic acid, then incubated at 100°C for 1 hour. The reaction was terminated by transferring the tubes to an ice bath, followed by the addition of 4.0 ml of toluene and vigorous mixing for 15-20 seconds. The toluene layer containing the chromophore was separated, brought to room temperature, and its absorbance measured at 575 nm using UV–Vis spectrophotometer model PLUS-B30 brand name-Labtron. A reagent blank was maintained, and a standard curve was created using 5 mg

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

of proline dissolved in 10 ml of 0.1 N hydrochloric acid. The proline content was expressed as mg g^{-1}fresh weights(Bates et al., 1973).

The total SOD activity was measured by assessing the enzyme's ability to inhibit the photochemical reduction of nitroblue tetrazolium (NBT) by the enzyme. To the reaction mixture (3mL), comprising 13.33mM methionine, 75µM NBT, 0.1mM EDTA, 50mM phosphate buffer (pH 7.8), 50mM sodium carbonate, and 0.1mL of enzyme extract, 0.1 mL of 2mM riboflavin was added. The reaction was initiated by placing the tubes under two 15W fluorescent lamps for 15 minutes. The absorbance was then measured at 560nm using UV–Vis spectrophotometer model PLUS-B30 brand name-Labtron, One unit of enzyme activity defined as the amount of enzyme required to decrease the absorbance by 50% compared to control tubes without the enzyme (Dhindsa et al., 1981; Sarker and Oba, 2018). The results are expressed in units $mg^{-1}$of protein.

For K and Na concentration analysis, dried samples of roots and shoots were ground. Approximately 0.1 to 0.15 g of dried, ground sample was placed in 20-mL scintillation vials. Then, 10 mL of 1 N hydrochloric acid was added to each vial, ensuring the sample remained completely submerged without vigorous shaking. The vials were then gently shaken for 16 hours at room temperature (20°C). After shaking, the samples were filtered into 100-mL volumetric flasks and diluted to a final volume of 100 mL with deionized water. The concentrations of K^+ and Na^+ were determined by a flame photometer using an exponential calibration curve (Asch et al., 2022). The Na^+/K^+ ratio was then calculated.

Statistical analysis was performed using MATLAB software, following a Completely Randomized Design (CRD) with a significance level set at $p = 0.05$. The standard error of the difference (SEd) and the critical difference (CD) were utilized wherever statistically significant differences were detected.

Results

The performance of five flowering annuals selected for sodicity tolerance was evaluated through pot culture experiments using soil with varying Exchangeable Sodium Percentage (ESP) levels. Plant height measurements at 70 days after sowing ranged from 11 to 50 cm (*Table 1*). Among the flowering annuals, tallest height was recorded by *Gomphrena globosa* at 24 ESP was on par with *Gomphrena globosa* at40 ESP, *Celosia cristata* at16 and 24 ESP, *Tagetes erecta* at 24 ESP and *Amaranthus dubius* at 16 ESP.

The dry matter production by the different flowering annuals at 70 days after sowing ranged from 5.01 to 19.24 g pot^{-1} (*Table 1*). The highest dry matter production was recorded by *Amaranthus dubius* at ESPs of 16, comparable to that of *Gomphrena globosa* at 24 ESP, *Celosia cristata* at an ESP of 24, and *Tagetes erecta*at an ESP level of 24 ESP.

A total phenol content at 70 days after sowing ranged from 19 to 76 mg GAE g^{-1} (*Table 2*). The total phenol content increased in the flowering annuals grown in soils with an ESP of 24 except *Amaranthus dubius*. Highest phenol content was recorded by *Gomphrena globosa*, comparable to *Celosia cristata* and *Tagetes erecta*, all at an ESP of 24.

Phenolic compounds, with their electron-donating hydroxyl groups, alleviate stress caused by sodium by scavenging free radicals, converting them into less reactive species, and promoting the production of natural antioxidant molecules within cells (Lin et al., 2016). Additionally, phenolic compounds stimulate the biosynthesis of plant phenols, which increases during abiotic stress conditions such as water deficit, metallic stress, salinity, flood, light and high temperature.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

Table 1. *Effect of soil sodicity on plant height (cm) and dry matter production of flowering annuals at 70 DAS (pot culture experiment)*

Treatments	Plan height (cm)	Dry matter production (g pot^{-1})
Tagetes erecta- 16 ESP	35	11.66
Tagetes erecta- 24 ESP	42	18.48
Tagetes erecta- 32 ESP	35	15.60
Tagetes erecta- 40 ESP	30	15.64
Celosia cristata- 16 ESP	37	13.44
Celosia cristata- 24 ESP	40	18.08
Celosia cristata- 32 ESP	32	15.54
Celosia cristata-40ESP	30	12.60
Gomphrena globosa-16 ESP	23	11.66
Gomphrena globosa-24 ESP	44	18.48
Gomphrena globosa-32 ESP	42	15.64
Gomphrena globosa-40 ESP	37	15.60
Amaranthus dubius- 16 ESP	41	18.82
Amaranthus dubius- 24 ESP	16	6.72
Amaranthus dubius- 32 ESP	14	5.88
Amaranthus dubius- 40 ESP	13	5.46
SEd	2.2	1.46
CD	4.9	3.12

The phenolic acid content of flowering annuals at 70 days after sowing ranged from 10 to 44 CAE g^{-1} (*Table 2*). *Gomphrena globosa* recorded the highest phenolic acid content at an ESPof 24, comparable to *Tagetes erecta* at an ESP of 24.Phenolic acids, also known as phenol carboxylic acids, are aromatic compounds that feature both a phenolic ring and an organic carboxylic acid group. These acids are crucial in enhancing plant resistance. Phenolic substances, which can be released from seeds, roots, or through the decomposition of plant residues, have the ability to combat soil-borne pathogens and root-feeding insects. The production of plant phenols has been found to increase under mildly sodic conditions (Mandal et al., 2010).

At 70 days after sowing, proline content ranged from 1.62 to 6.84 mg g^{-1} of fresh weight (*Table 2*). Among the flowering annuals, *Gomphrena globosa* had the highest proline accumulation at an ESP of 24, similar to *Celosia cristata* and *Tagetes erecta*. Osmolytes, which are low-molecular-weight organic compounds, significantly impact the properties of biological fluids and are crucial in regulating osmotic pressure and maintaining cellular homeostasis, especially under environmental stress.

Proline, an amino acid, acts as an excellent osmolyte, metal chelator, antioxidative defense molecule, and signaling molecule, providing protection to plants under stress conditions. It mitigates salt stress by enhancing antioxidant activities, reducing the uptake and translocation of Na^+ and Cl^-, and promoting K^+ assimilation in plants (Moukhtari et al., 2020).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

Table 2. *Effect of soil ESP on total phenol content (mg GAE g^{-1}), Phenolic acid content (mg CAE g^{-1}), Proline content (mg g^{-1} of fresh weight) and superoxide dismutase activity (Units mg^{-1} of protein) of flowering annuals at 70 days after sowing*

Treatments	**Total phenol content (mg GAE g^{-1})**	**Phenolic acid content (mg CAE g^{-1})**	**Proline content (mg g^{-1} of fresh weight)**	**Superoxide dismutase activity (Units mg^{-1} of protein)**
Tagetes erecta- 16 ESP	52	35	4.68	66.9
Tagetes erecta- 24 ESP	73	42	6.57	94.0
Tagetes erecta- 32 ESP	61	35	5.49	78.5
Tagetes erecta- 40 ESP	52	30	4.68	66.9
Celosia cristata- 16 ESP	37	37	5.04	72.1
Celosia cristata-24ESP	40	40	6.75	96.5
Celosia cristata- 32 ESP	32	32	5.75	82.2
Celosia cristata-40ESP	30	30	4.68	66.9
Gomphrena globosa-16 ESP	48	23	4.32	72.1
Gomphrena globosa-24 ESP	76	44	6.84	96.5
Gomphrena globosa-32 ESP	65	40	5.85	66.9
Gomphrena globosa-40 ESP	64	37	5.76	82.2
Amaranthus dubius- 16 ESP	36	21	3.24	46.3
Amaranthus dubius- 24 ESP	28	16	2.52	36.0
Amaranthus dubius- 32 ESP	24	14	2.16	30.9
Amaranthus dubius- 40 ESP	23	13	2.07	29.6
SEd	1.9	1.81	0.42	1.47
CD	4.1	3.91	0.90	3.15

The superoxide dismutase activity (SOD) of flowering annuals at 70 days after sowing ranged from 25 to 97.8 units mg^{-1} of protein (*Table 2*). Among the flowering annuals, *Gomphrena globosa* exhibited higher SOD activity, comparable to *Celosia cristata* at an ESP of 24.

To counteract the effects of reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, and singlet oxygen, various classes of antioxidants help plants tolerate different stressors (Hasanuzzaman et al., 2020). Superoxide dismutase (SOD) is a key class of antioxidant proteins that serves as a primary defense against these stressors (Jomova et al., 2024).

APPLIED ECOLOGY AND ENVIRONMENTAL RESEARCH 23(2):2425-2439.
http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

In the present study, root length of the flowering annuals in soils with different ESP ranged from 9.4 to 31.1 cm (*Table 3*). *Gomphrena globosa* exhibited greater root length, comparable to *Celosia cristata* and *Tagetes erecta*, at 24 ESP.

Table 3. *Effect of sodicity levels on root length (cm), Root volume (cm^3) and VAM propagules (mg g^{-1}) of soil of flowering annuals at 70 days after sowing*

Treatments	**Root length (cm)**	**Root volume (cm^3)**	**VAM propagates (mg g^{-1}) of soil**
Tagetes erecta- 16 ESP	21.3	11.4	46.80
Tagetes erecta- 24 ESP	29.9	12.2	65.70
Tagetes erecta- 32 ESP	25.0	14.1	54.90
Tagetes erecta- 40 ESP	21.3	11.4	46.80
Celosia cristata- 16 ESP	22.9	10.7	50.40
Celosia cristata-24ESP	30.7	11.4	67.50
Celosia cristata- 32 ESP	26.1	12.2	57.50
Celosia cristata-40ESP	21.3	11.5	46.80
Gomphrena globosa-16 ESP	19.6	17.0	43.20
Gomphrena globosa-24 ESP	31.1	19.7	68.40
Gomphrena globosa-32 ESP	26.6	11.7	58.50
Gomphrena globosa-40 ESP	26.2	10.9	57.60
Amaranthus dubius- 16 ESP	14.7	12.4	32.40
Amaranthus dubius- 24 ESP	11.5	13.1	25.20
Amaranthus dubius- 32 ESP	9.8	11.4	21.60
Amaranthus dubius- 40 ESP	9.4	9.2	20.70
SEd	1.20	1.22	1.53
CD	2.57	2.61	3.27

Root activity is greatly influenced by the environmental conditions of the root zone. When plant roots are exposed to sodium ion toxicity, they experience an increase in the respiratory costs needed for maintenance, active ion transport, and growth processes. This leads to a high rate of root respiration despite a reduced growth rate (Nakamura and Nakamura, 2016).

Sodium poses challenges to plants by causing water stress, malnutrition, and potentially toxic ion accumulation. To increase tolerance, plants have developed mechanisms such as sodium exclusion, compartmentation, and osmoregulation. Overall tolerance, however, is the result of the combined effects of these mechanisms operating at cellular, tissue, and organ levels. Roots, being in direct contact with the soil solution, are the first to encounter excess sodium and thus serve as the initial sites for potential damage or defense (Hasanuzzaman and Fujita, 2022).

Root volume of flowering plants at 70 days after sowing ranged from 5.1 cm^3 to 19.7 cm^3 (*Table 3*). *Gomphrena globosa* showed increased root volume when grown in soil with an ESP of 24, followed by growth at an ESP of 16. In the present study, *Gomphrena globosa* possessed higher root volume than the other flowering annuals, serving as a mechanism to tolerate sodium stress.

In the present study vesicular-arbuscular mycorrhizae (VAM) propagules of soil with different ESP levels grown with different flowering annuals ranged from 16.54 to 68.4 mg $kg^{-1}$of soil.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

Significant differences were observed among flowering annuals grown in soils with varying ESP levels. *Gomphrena globosa* showed a higher number of VAM propagules at an ESP of 24, comparable to *Celosia cristata* and *Tagetes erecta* under the same conditions. Vesicular-arbuscular mycorrhizae (VAM) are mycorrhizal fungi that form symbiotic relationships with the roots of most terrestrial plants. These fungi are crucial for enhancing plant growth and stress tolerance by improving nutrient and water uptake, particularly in challenging soil conditions. VAM helps the plants to withstand various environmental stressors, such as drought, salinity, and nutrient deficiencies, by expanding root surface area and facilitating access to otherwise unavailable soil resources. Under stress conditions, mycorrhizae support plants in nutrient uptake and overall stress tolerance.

The yield of flowering annuals ranged from 18.0 to 69.5 grams per pot (*Table 4*). This yield is important in determining the economic viability for farmers. An increased yield was recorded for *Celosia cristata* at 24 ESP, which was on par with *Gomphrena globosa* at 24 ESP. The increased yield of *Celosia cristata* and *Gomphrena globosa* at 24 ESP can be attributed to several key factors.

Table 4. *Effect of different sodicity levels on yield (g pot^{-1}) of flowering annuals*

Treatments	Yield (g pot^{-1})	% increase over control
Tagetes erecta- 16 ESP	46.8	0.00
Tagetes erecta- 24 ESP	65.7	0.29
Tagetes erecta- 32 ESP	54.9	0.17
Tagetes erecta- 40 ESP	46.8	0.00
Celosia cristata- 16 ESP	51.8	0.11
Celosia cristata-24 ESP	69.5	0.49
Celosia cristata- 32 ESP	59.5	0.27
Celosia cristata-40ESP	48.8	0.04
Gomphrena globosa-16 ESP	43.2	-0.08
Gomphrena globosa-24 ESP	68.4	0.46
Gomphrena globosa-32 ESP	58.5	0.25
Gomphrena globosa-40 ESP	57.6	0.23
Amaranthus dubius- 16 ESP	32.4	-0.31
Amaranthus dubius- 24 ESP	25.2	-0.46
Amaranthus dubius- 32 ESP	21.6	-0.54
Amaranthus dubius- 40 ESP	20.7	-0.56
SEd	0.78	
CD	2.71	

Firstly, 24 ESP might represent an optimal level of environmental stress that stimulates plant growth and flowering without causing significant damage or inhibition, striking a balance that leads to higher productivity. Secondly, adequate nutrient availability at 24 ESP can enhance plant metabolism and growth, leading to higher yields by ensuring that the plants receive essential minerals and elements necessary for robust development. Additionally, these plants may have developed tolerance mechanisms that allow them to thrive under certain levels of environmental stress. These mechanisms could include enhanced antioxidant activity to combat oxidative stress, osmotic adjustment to maintain

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DOI: http://dx.doi.org/10.15666/aeer/2302_24252439

cell turgor under low water availability or high sodicity, and improved water use efficiency to sustain growth and yield under suboptimal moisture conditions. Collectively, these factors create a favorable environment for the flowering annuals, resulting in increased yields and better economic returns for farmers.

In this study, Sodium (Na^+) ion content ranged from 31 to 42 mg g^{-1} of dry weight (*Table 5*).*Celosia cristata* and *Gomphrena globosa* showed the lowest Na+ content at 16 ESP. *Amaranthus dubius* recorded the highest Na+ ion content at 40 ESP, followed by the same species at 32 and 24 ESP. Exposure of plants to high levels of Na^+ in the soil leads to wilted foliage and stunted growth because excessive sodium impedes water uptake, resulting in dry and discolored tissues. Additionally, moderate sodium levels can slow growth without causing visible symptoms.

Table 5. *Effect of different sodicity levels on Na^+ content (mg g^{-1} of DW), K^+ content (mg g^{-1} of DW) and Na/K ratio of flowering annuals at 70 days after sowing*

Treatments	Na^+ content (mg g^{-1} of DW)	K^+ content (mg g^{-1} of DW)	Na/K ratio
Tagetes erecta- 16 ESP	34	50	0.68
Tagetes erecta- 24 ESP	36	53	0.68
Tagetes erecta- 32 ESP	38	36	1.06
Tagetes erecta- 40 ESP	38	30	1.27
Celosia cristata- 16 ESP	31	50	0.62
Celosia cristata - 24 ESP	34	52	0.65
Celosia cristata- 32 ESP	35	36	0.97
Celosia cristata-40 ESP	36	28	1.29
Gomphrena globosa-16 ESP	32	48	0.67
Gomphrena globosa-24 ESP	33	50	0.66
Gomphrena globosa-32 ESP	34	36	0.94
Gomphrena globosa-40 ESP	36	28	1.29
Amaranthus dubius- 16 ESP	38	48	0.79
Amaranthus dubius- 24 ESP	40	36	1.11
Amaranthus dubius- 32 ESP	40	30	1.33
Amaranthus dubius- 40 ESP	42	28	1.50
SEd	0.7	0.5	0.21
CD	1.5	1.0	0.45

Potassium (K^+) content by the flowering annuals ranged from 28 to 53 mg g^{-1} of dry weight (*Table 5*). *Tagetes erecta* and *Celosia cristata* both exhibit significant K^+ content at 24 ESP, with *Tagetes erecta* showing the highest levels. On the other hand, *Celosia cristata*, *Gomphrena globosa*, and *Amaranthus dubius* recorded the lowest K^+ ion content at 40 ESP level. Potassium is crucial for maintaining the overall health of plants, aiding in their resilience against biotic stress, and improving quality factors like seed or grain size, shape, color, and vigor. At higher ESP levels, the reduced availability of K^+ may impair physiological activities, leading to the lower observed K^+ content in some species at 40 ESP.

Sodium ratio (Na+/K+)in the present study ranged from 0.62 to 1.50 (*Table 5*). A low sodium ratio was recorded for *Celosia cristata*, *Tagetes erecta*, *Gomphrena globosa*, and *Amaranthus dubius* at 16 and24 ESP. Sodium tolerances in plants is characterized by their

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ability to maintain high potassium ion content and low sodium ion content in tissues compared to sensitive plants, typically indicated by the Na^+/K^+ ratio. Higher Na^+ ratios were observed in *Tagetes erecta* at 40 and 32 ESP, *Gomphrena globosa* and *Celosia cristata* at 40 ESP, and *Amaranthus dubius* at 40, 32, and 24 ESP. This increase is due to higher sodium saturation in the soil at elevated ESP levels, which displaces essential cations like K^+ and Ca^{2+}, reducing their availability and leading to greater Na^+ uptake. Osmotic stress further drives this uptake to maintain cell turgor. Species-specific traits also influence these patterns; for example, *Amaranthus dubius* tolerates higher Na^+ by compartmentalizing it in vacuoles, while other species may employ selective ion uptake mechanisms.

Salient findings

The study evaluated the sodicity tolerance of five flowering annuals using pot culture experiments with varying Exchangeable Sodium Percentage (ESP) levels. At 70 days after sowing, plant heights ranged from 13 to 44 cm, with *Amaranthus dubius* reaching the tallest at 16 ESP and *Gomphrena globosa* at 24 ESP. Dry matter production varied from 5.46 to 18.48 g per pot, with *Amaranthus dubius* performing best at 16 ESP, comparable to *Gomphrena globosa* and *Celosia cristata* at 24 ESP.

Total phenol content, which helps alleviate sodium stress, ranged from 23 to 76 mg GAE g^{-1}, with *Gomphrena globosa* recording the highest at 24 ESP. Phenolic acid content also peaked with *Gomphrena globosa* at 24 ESP. Proline content, aiding in stress protection, varied from 2.07 to 6.84 mg g^{-1}, with *Gomphrena globosa* highest at 24 ESP. Superoxide dismutase (SOD) activity ranged from 29.6to 96.5 units mg^{-1}, with *Gomphrena globosa* showing the highest at 24 ESP.

Root length and volume were greatest in *Gomphrena globosa* at 24 ESP. VAM propagules were highest in *Gomphrena globosa* at 24 ESP. Yield ranged from 20.7 to 69.5 g per pot, with *Celosia cristata* and *Gomphrena globosa* performing best at 24 ESP. Na^+ ion content was lowest in *Celosia cristata* and *Gomphrena globosa* at 16 ESP, while potassium uptake peaked in *Tagetes erecta* and *Celosia cristata* at 24 ESP. The Na^+/K^+ ratio was lowest in *Celosia cristata* at 16 ESP.

Conclusion

Based on the results of the pot culture experiment, it can be concluded that *Gomphrena globosa* and *Celosia cristata* are highly suitable for sodic soils up to an ESP of 24. These plants demonstrated superior growth, higher dry matter production, better stress tolerance, favorable sodium-to-potassium ratios, and higher yields compared to the other species tested. This makes them ideal candidates for cultivation in sodic soil conditions, providing a viable option for areas affected by high soil sodicity.

Acknowledgement. The author acknowledged university officials for providing necessary facilities for conducting the experiment.

Conflict of interest. The author also declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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DOI: http://dx.doi.org/10.15666/aeer/2302_24252439