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Evaluation of *Sesuvium portulacastrum* for the Phytodesalination of Soils Irrigated over a Long-Term Period with Paper Mill Effluent under Non-leaching Conditions

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Paper and pulp mills discharge large volumes of wastewater into the environment. Crop productivity can be improved by using this wastewater, which is rich in salts and nutrients, as an irrigation source improves crop productivity by supplying enormous amount of nutrients. But for a long termit leads to development of soil salinity and sodicity and also calcareousness. Since leaching of salt affected soils with good quality water is impossible because of its non-availability in the study area, an attempt was made in the present study with the technique of phytodesalinisation using halophytes for remediation. *Sesuvium portulacastrum,* a facultative halophyte is widely studied for its phyto-desalinisation capacity of salt affected soils. Hence, present work was carried out to evaluate the *S. portulacastrum* for desalinization of saline-sodic soils of long term treated paper mill effluent irrigating soils. The halophyte found to have maximum sodium absorption and reduced the soil salinity considerably with 56.8 per cent reduction in ECe of the soil. A pot experiment was conducted in the long term treated effluent irrigating soils using good quality irrigation water and treated effluent as a source of irrigation. The cultivation of *S. portulacastrum* under treated effluent irrigating soils showed significant absorption of sodium ions and their accumulation in the shoot portion with the leaves having the highest Na and Cl content. Physiological, anatomical and biochemical studies showed the tolerance potential of *S. portulacastrum* to salt stress by accumulating osmolytes. Thus *S. portulacastrum* may possibly an ideal candidate for reclamation of salinity induced by treated paper mill effluent irrigation.

Introduction

The paper and pulp industry is one of the largest industries in the world and consumes large quantities of water. Nearly 75%–95% of the fresh water used in a paper and pulp mill is discharged as wastewater into the environment. The paper and pulp industry is categorised as one of the 17most polluting industries in India (Sharma *et al.,* 2014).

According to the technology adopted, 72–225 m^3wastewater is released per ton of paper produced (Tripathi *et al.,* 2014). This wastewater is used as an irrigation source because it contains supplementary nutrients (Rezende *et al.,* 2010). Generally, the wastewater from a pulp and paper mill is alkaline, with a pH ranging from 7.2 to 9.4.It has a high electrical conductivity. The wastewater contains a high concentration of sodium chloride and appreciable concentration of carbonate and bicarbonate. It exhibits a tendency to precipitate calcium in the soil as $CaCO_3$.Thus, the waste water increases the proportion of sodium to calcium and magnesium and the sodium adsorption ratio of the soil solution (Sharma *et al.,* 2014), which leads to the development of salinity, sodicity, and calcareousness.

Saline–sodic soils can be reclaimed to an extent by removing the saline soil and replacing monovalent sodium ions with divalent cations, such as calcium, to improve the soil quality and crop productivity. A conventional technique for reclaiming saline–sodic soils involves leaching the soil with good-quality water to remove excess saline salts (Abrol *et al.,* 1988) and applying gypsum as an amendment. Phytoremediation is an alternate technique that involves using plants to remove, accumulate, transform, or diminish contaminants in soil (Kömives and Gullner, 2000). Phytoextraction is an important method for the phytoremediation of salt-affected soils. Phytoextraction involves using plants to store salt in shoots. The salt can then be removed from the soil by harvesting the plants/above ground biomass (Laboratory, 2000). Although a high salt concentration aids the growth of halophytes, where as it is toxic to glycophytes (Messedi *et al.,* 2004), by disturbing their metabolic functions (Lokhande *et al.,* 2010). To overcome the surplus salt conditions, halophytes possess several adaptation mechanisms, such as exclusion, compartmentalisation of toxic ions (Hasanuzzaman *et al.,* 2014), or utilization of osmoprotectants (Coll *et al.,* 1998). Halophytes present in chloride-rich environments possess succulent morphology with chloride ions accumulated in the cytoplasm. Halophytes lack succulent morphology when there exists a shortage of chloride ions in them. These adaptations allow halophytes to obtain the water essential for their survival from the soil.

Sesuvium portulacastrum L. is a multipurpose facultative halophyte that belongs to the Aizoaceae family. *S. portulacastrum L*. may be an ideal candidate for the phytoremediation of salt-affected soil because it forms even in poor nutrient conditions and can also be used as forage for cattle (Lokhande and Suprasanna, 2012); (Rabhi *et al.,* 2010). *S. portulacastrum* can accumulate excess Na^+ in the vacuoles by increasing the size of vacuoles and maintaining cytosolic metabolism (Lokhande and Suprasanna, 2012). Moreover, the accumulation of proline in large amounts as an osmoprotectantis a major salt adaptation mechanism (Moseki and Buru, 2010).Several studies have proved the desalination efficiency of *S. portulacastrum* in salt-affected soils under nonleaching conditions (Rabhi *et al.,* 2010; Ravindran *et al.,* 2007). Few studies have also proved the desalination efficiency of *S. portulacastrum* in industrial-waste-water-affected soils (Sundararaj *et al.,* 2014; Ramesh Kannan *et al.,* 2009).

The aim of this study was to identify a suitable method for remediating salt-affected soils (saline–sodic soils) irrigated for a long-term period with paper mill effluent. Leaching salts with good-quality water is impossible in the study area. Hence, phytodesalination was performed with *S. portulacastrum*. The salt removal mechanism and growth response of *S. portulacastrum* were investigated by determining the physiological and biochemical parameters of the halophyte.

Materials and Methods

Soil and plant material

The soil samples required for the study were collected from the soil areas irrigated with paper and pulp mill effluent for a long-term period. The samples were collected from locations at latitudes between 11.01°Nand 11.50°Nand longitudes between 77.987°E and 78.012°E.Pichavaram is the second largest mangrove forest in the world, and the salty marsh area of Pichavaram is a habitat for many types of obligate and facultative halophytes.

Hyper-salt-accumulating *S. portulacastrum* samples were collected for remediating the salt-contaminated soils from Pichavaram forest. The collected hyper-salt-accumulating plant was identified and confirmed as *S. portulacastrum* through the Botanical Survey of India, Coimbatore. The collected plants were multiplied under optimum conditions. *S. portulacastrum* cuttings of three to four leaves without roots (approximately 5–7 cm in size) were used as planting material for phytodesalination.

Treatments

To study the phytodesalination efficiency of *S. portulacastrum* for soils irrigated with treated paper mill effluent, treatments were performed with and without the halophyte. Moreover, the treated paper and pulp mill effluent was used as an irrigation source with 36 replications. An adequate amount of soil was shade-dried. Large debris were removed. Subsequently, 10 kg soil was transferred to nonperforated pots to prevent the leaching of salts from the soil. Four *S. portulacastrum* cuttings were planted in each pot (Fig. 1–3).

A second experiment was performed to study the changes in the salinisation after irrigation with treated effluent (T_1) and good-quality water (T_2). The effect of salinisation on the physiological and biochemical parameters of *S. portulacastrum* in saline–sodic soils was also determined. An adequate amount of soil was shade-dried, large debris were removed, and subsequently 10 kg soil was transferred to nonperforated pots to prevent the leaching of salts from the soil. F our *S. portulacastrum* cuttings were planted in each pot.

In both the experiments, irrigation was performed according to the field capacity of the soil (22.5%), which was estimated using a pressure plate apparatus (Obi, 1974). The initial weight of the pots after irrigation source addition based on FC was noted. The pots were weighed each time before irrigation, and a reduction in the weight was considered as a requirement for maintaining the field capacity of the soil. The physiological and biochemical measurements were performed 30 days after planting. Studies have indicated that after 90 days, a decrement occurs in the biomass productivity and salt uptake due to the ageing, disintegration, or nonavailability of nutrients (Sundararaj *et al.*, 2014). Hence, *S. portulacastrum* was grown for 90 days and then harvested.

Soil analysis

The soil samples obtained before and after the experiment were shade-dried and processed using a 2-mm sieve before the analysis. The soil texture was identified according to the protocol of ISSS (Science, 1929). The pH and ECe were estimated in saturation paste extracts. The soil organic carbon was estimated using the wet digestion method (Walkley and Black, 1934).

The available nitrogen and phosphorus were estimated using the methods of (Subbiah and Asija, 1956) and (Olsen *et al.*, 1954), respectively. The sodium and potassium content was estimated using flame photometry (Stanford and English, 1949),whereas the calcium and magnesium content was estimated through the Versenate method (Jackson, 1973).

Plant analysis

The leaves, stem, and root of the plant samples were separated from each other and then weighed, oven-dried, and ground to determine the plant ion composition.

Completely expanded fresh leaf samples were harvested between 8.00 and 9.00 am (carried using an ice box) to obtain the biochemical and physiological parameters, such as the free proline content(Bates *et al.,* 1973).

The total soluble sugars was estimated using the anthrone method (Watanabe *et al.,* 2000). The electrolyte leakage rate (ELR) and chlorophyll content were evaluated through the methods of Lutts (Lutts *et al.,* 1995) and Lichtenthaler (Lichtenthaler, 1987), respectively. The lipid peroxidation in terms of the malondialdehyde (Majumdar *et al.,*) content was also determined (Heath and Packer, 1968).

Na^+ and K^+ were assayed through flame emission spectrophotometry (Labtronics, LT671) after triacid extraction (HNO_3:H_2SO_4:$HClO_4$–9:2:1) of the finely grounded dry matter of the leaf, stem, and root samples. Ca^{2+} and Mg^{2+} were analysed through the Versenate method by using the acid extract.

Statistical analysis

The statistical parameters, namely the mean, standard devaiton (Havlin *et al.,* 2005), and standard error (SE) for the physicochemical parameters were determined using SPSS Version 16.

The mean and SDs were calculated to determine the chemical parameters that deviated from the standards.

Results and Discussion

Characteristics of the soil and irrigation water

The soil used in the experiment belongs to the Vannapatti series, is a member of the Typic Ustorthents category, and is classified as red loamy sand (sand: 71%, silt: 20%, and clay: 9%).The soil is highly saline–sodic and has a pH of 8.17, ECe of 4.57 dSm^{-1}, and exchangeable sodium percentage (Zafrilla *et al.,*) of 33.93%. The soil has a medium organic carbon content (0.56%), low available nitrogen content, and high available phosphorus and potassium content.

The treated paper mill effluent had a high salt (especially sodium and chloride) and bicarbonate content. The characteristics of the effluent were within the requirements of the Indian Central Pollution Control Board (CPCB) standards of industrial wastewater for inland surface irrigation (Table 2).

Phytodesalination of effluent-irrigated soil

The continuous addition of treated effluent in the soil as an irrigation source considerably increased the salinity and sodicity (Tables 1 and 3), which indicates that the salt stress increased during the growth period of the plant.

The initial ECe (EC from the saturation paste extract) was 4.57 dSm^{-1}. However, the ECe significantly reduced to 3.01 dSm^{-1}at 90 DAP for the *S. portulacastrum* cuttings. The ECe increased to 6.97 dSm^{-1} on the addition of treated effluent (without halophyte; Table 3). A 56.8% reduction in the ECe of the soil occurred due to phytodesalination with

Sesuvium, whereas a 52.5% increase in the ECe of the soil was observed in the treatment without halophyte. Thus, the phytodesalination capacity of *S. portulacastrum* under nonleaching conditions was verified (Rabhi *et al.,* 2010).

On phytodesalination, a 37% and 33% reduction was observed in the number of exchangeable sodium and chloride ions, respectively. On treatment without the halophyte, the number of exchangeable sodium and chloride ions increased by 37.5% and 40.6 %, respectively. A 22%reduction was observed in the ESP of the phytodesalinsed soil. An increase of 4.7%was noted in the ESP of the soil treated without the halophyte. Thus, *Sesuvium* accumulated a larger amount of sodium ions than other cations, which led to a significant reduction in the ESP. Ramasamy *et al.*,(Ramasamy *et al.*, 2017) used *S. portulacastrum* to remediate soil contaminated by dye and textile effluent. In their study, the EC of the soil reduced from 13.04 to 7.37 dSm^{-1} 30 days after planting. The EC further reduced to 5.34 dSm^{-1}60 days after planting, with increased plant and biomass growth. After 90 days, 77.8% of the sodium content of the soil was removed. Similarly, Rabhi *et al.*, (Rabhi *et al.*, 2010) observed that phytodesalination with *Sesuvium* led to a 37% decrease in the ECe of the upper horizon.

Growth

Under salt stress, *S. portulacastrum* exhibits various adaptations, including morphological, physiological, and biochemical modifications (Lokhande and Suprasanna, 2012). A significant increase in the shoot length, root length, and biomass was observed in plants grown with the treated effluent (Table 4).

A similar salt-induced growth was reported by Missedi *et al.,* (2004) at a concentration of 100–400 mMNaCl. In their study, the plant growth stabilized at 800 mM. In the pot culture experiment, fresh biomass was produced at the rate of 8 ton per hectare in the soil irrigated with the treated effluent. In total, 24.2 L of effluent was used for irrigation during the 90-day period. The increased growth of *S. portulacastrum* on effluent addition may be due to the increased succulence, large nutrient supply, and optimum sodium content, which favour the growth of halophytes.

Membrane damage

Halophytes with a succulent morphology accumulate a higher volume of sodium in the vacuoles than in the cytoplasm (Hagibagheri and Clipson, 1986). However, due to the high salt stress, oxidative stress is developed, leading to the production of reactive oxygen species (ROS),which damage the lipids, proteins, and nucleic acid in plant cells (Skopelitis *et al.,* 2006). The ELR was determined to ascertain the rate of membrane damage due to oxidative stress. On the continuous addition of treated effluent loaded with salts might had highest oxidative damage with 92% ELR compared with good-quality water irrigation @ 90 DAP compared to @ 30 DAP. An increased electrolyte leakage indicated increased electrolyte leaching from the cell to the external solution. The MDA content was also considerably higher in the effluent-irrigated treatments (T_1) than in the samples irrigated with good-quality water. In T_1, the MDA content increased at 90 DAP. Moreover, the MDA content at 60 DAP was marginally lower than that at 30 DAP. In T_2, agradual increase in the MDA content was observed; however, the increase was not at a significant level.

Osmolyte accumulation

Osmotic stress due to salinity leads to a reduced water level and disruption in protein stability.

Table.1 Initial characteristics of the soil used in the experiment

Parameters	Initial
ECe (dSm^{-1})	4.57
pH	8.17
ESP	33.9
Organic Carbon (%)	0.56
Available Nitrogen ($kgha^{-1}$)	156
Available Phosphorus ($kgha^{-1}$)	26.5
Available Potassium ($kgha^{-1}$)	330
Exchangeable Calcium (cmol (p^+) kg^{-1})	6.80
Exchangeable Magnesium (cmol (p^+) kg^{-1})	2.60
Exchangeable Sodium (cmol (p^+) kg^{-1})	5.04
Exchangeable Potassium (cmol (p^+) kg^{-1})	0.42
Exchangeable Chloride (cmol (p^+) kg^{-1})	0.24
Exchangeable Bicarbonate (cmol (p^+) kg^{-1})	0.54
Soil Type	Saline–Sodic

Table.2 Characteristics of the treated effluent water used for irrigation

Parameters	Values	CPCB Standards of Irrigation Water, 1995
Total Dissolved Solids (mgL^{-1})	1860	2100
Total Suspended Solids (mgL^{-1})	100	200
pH	8.01	5.5–9
Electrical Conductivity (dSm^{-1})	3.57	-
Biochemical Oxygen Demand(mgL^{-1})	31.4	100
Chemical Oxygen Demand(mgL^{-1})	251	-
Organic Carbon (%)	0.56	-
Total Nitrogen(mgL^{-1})	252	-
Total Phosphorus (mgL^{-1})	213	-
Total Potassium (mgL^{-1})	390	-
Calcium (mgL^{-1})	228	-
Magnesium (mgL^{-1})	28.8	-
Sodium (mgL^{-1})	541	-
Chloride (mgL^{-1})	602	-
Sulphate (mgL^{-1})	90.6	-
Carbonate (mgL^{-1})	36.0	-
Bicarbonate (mgL^{-1})	292	-

Table.3 Changes in the physicochemical parameters on effluent water addition and remediation by *S. portulacastrum* (90^{th} day)

Parameters	Without Halophyte	With Halophyte (90 DAP)
ECe (dSm^{-1})	6.97	3.01
pH	7.25	7.21
ESP	35.53	27.73
Organic Carbon (%)	0.57	0.56
Available Nitrogen (kgha−1)	165	161.2
Available Phosphorus ($kgha^{-1}$)	19.8	21.6
Available Potassium ($kgha^{-1}$)	481	358.8
Exchangeable Calcium (cmol (p^+) kg^{-1})	8.89	8.40
Exchangeable Magnesium (cmol (p^+) kg^{-1})	3.18	2.50
Exchangeable Sodium (cmol (p^+) kg^{-1})	6.93	4.36
Exchangeable Potassium (cmol (p^+) kg^{-1})	0.61	0.46
Exchangeable Chloride (cmol (p^+) kg^{-1})	0.32	0.19
Exchangeable Bicarbonate (cmol (p^+) kg^{-1})	0.57	0.53

Table.4 Effect of treated effluent and good-quality irrigation water on the shoot length, root length, and biomass at 30, 60, and 90 DAP

	Shoot Length (cm)				Root Length (cm)				Fresh Biomass ($gpot^{-1}$)			
	Initial	30 DAP	60 DAP	90 DAP	Initial	30 DAP	60 DAP	90 DAP	Initial	30 DAP	60 DAP	90 DAP
Treated Effluent (T_1)	5.3±0.89	21.6±1.49	30.6±2.25	58.8±3.25	-	12.1±3.25	18.5±2.85	22.9±2.44	28±1.02	164±2.34	222.6±2.45	320±2.35
Good-Quality Water (T_2)	5.3±0.89	18.5±2.18	26.8±3.12	55.6±3.03	-	8.1±4.10	12.3±3.65	18.6±3.45	28±1.02	160.3±1.77	220.3±1.64	311.5±2.05

*Values represent the means of 10 replicatesand the SE at 5%.

Table.5 Effect of treated paper mill effluent and good-quality water on the physiological and biochemical parameters of *Sesuvium*

Parameters	Effluent-Treated (T_1)			Good-Quality Water (T_2)		
	30 DAP	**60 DAP**	**90 DAP**	**30 DAP**	**60 DAP**	**90 DAP**
Leaf Proline (μg^{-1} FW)	643±2.5	655±1.84	677±2.12	222±1.42	233±2.06	246±2.45
Membrane Permeability (ELR)	69.2±0.72	89.3±0.98	91.8±1.05	46.2±1.35	57.0±0.75	61.8±2.33
Total Sugars (mg g^{-1} FW)	22.2±0.38	25.1±1.45	17.4±1.9	26.9±1.17	17.3±1.33	11.5±3.02
MDA Content (µmol g^{-1} FW)	1.11±0.60	0.79±2.01	3.67±1.11	0.65±0.84	0.78±0.99	0.94±1.35
Chlorophyll a (mg g^{-1})	1.01±0.65	0.79±1.65	0.33±1.32	0.85±1.20	0.53±0.98	0.30±1.61
Chlorophyll b (mg g^{-1})	0.98±0.54	0.52±1.24	0.18±0.92	0.76±1.32	0.49±1.20	0.14±1.11
Total Chlorophyll (mg g^{-1})	1.99±1.09	1.31±2.89	0.50±2.24	1.62±0.98	1.02±2.18	0.44±2.72

*Values represent the means of 10 replicatesand theSE at 5%.

Fig.1 Experiment with and without *S. portulacastrum*

Fig.2 Ion composition of *S. portulacastrum* treated with (a) effluent and (b) good-quality water after 30days. The values represent the means of three replicates and the SE at 5%

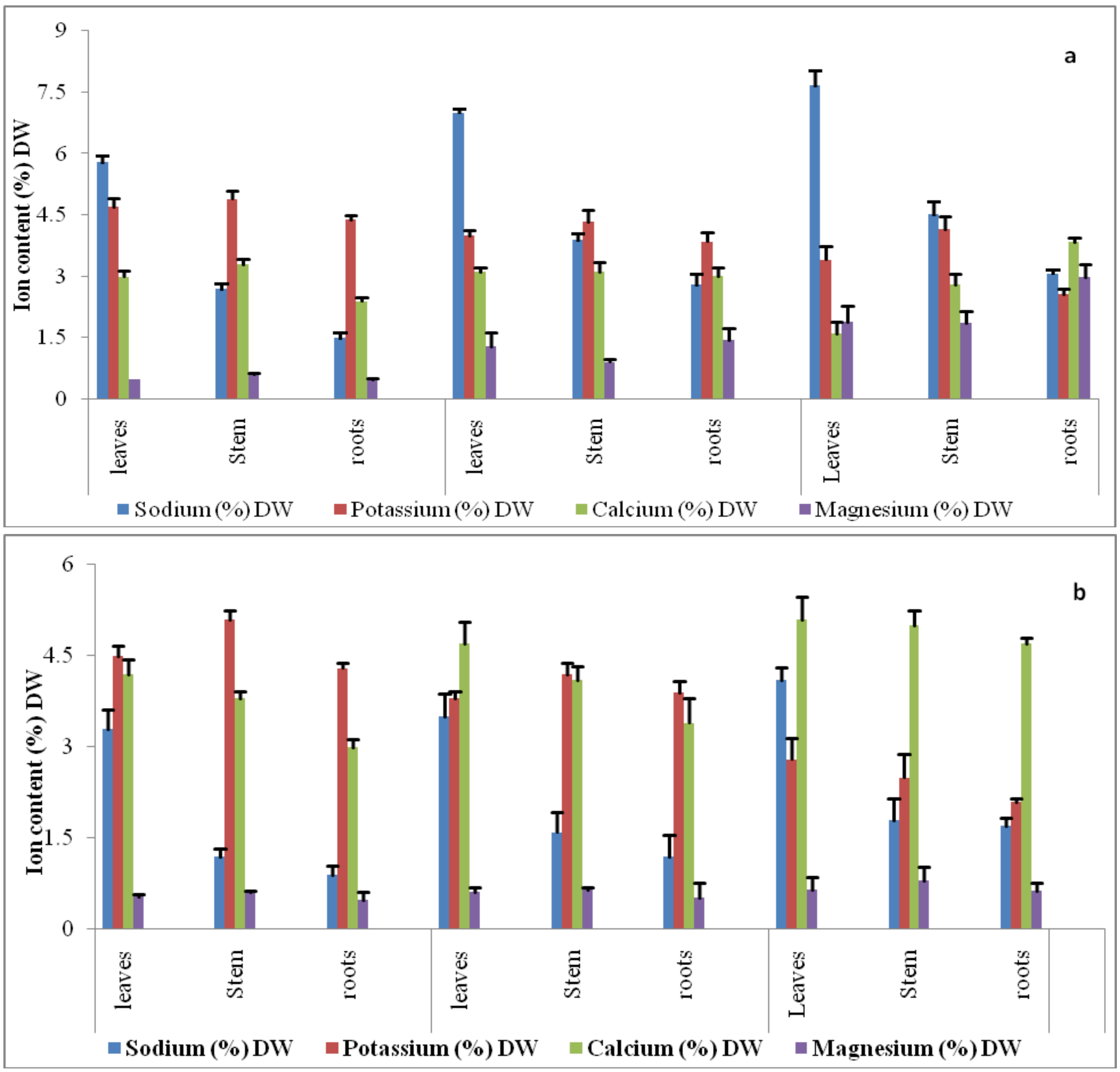
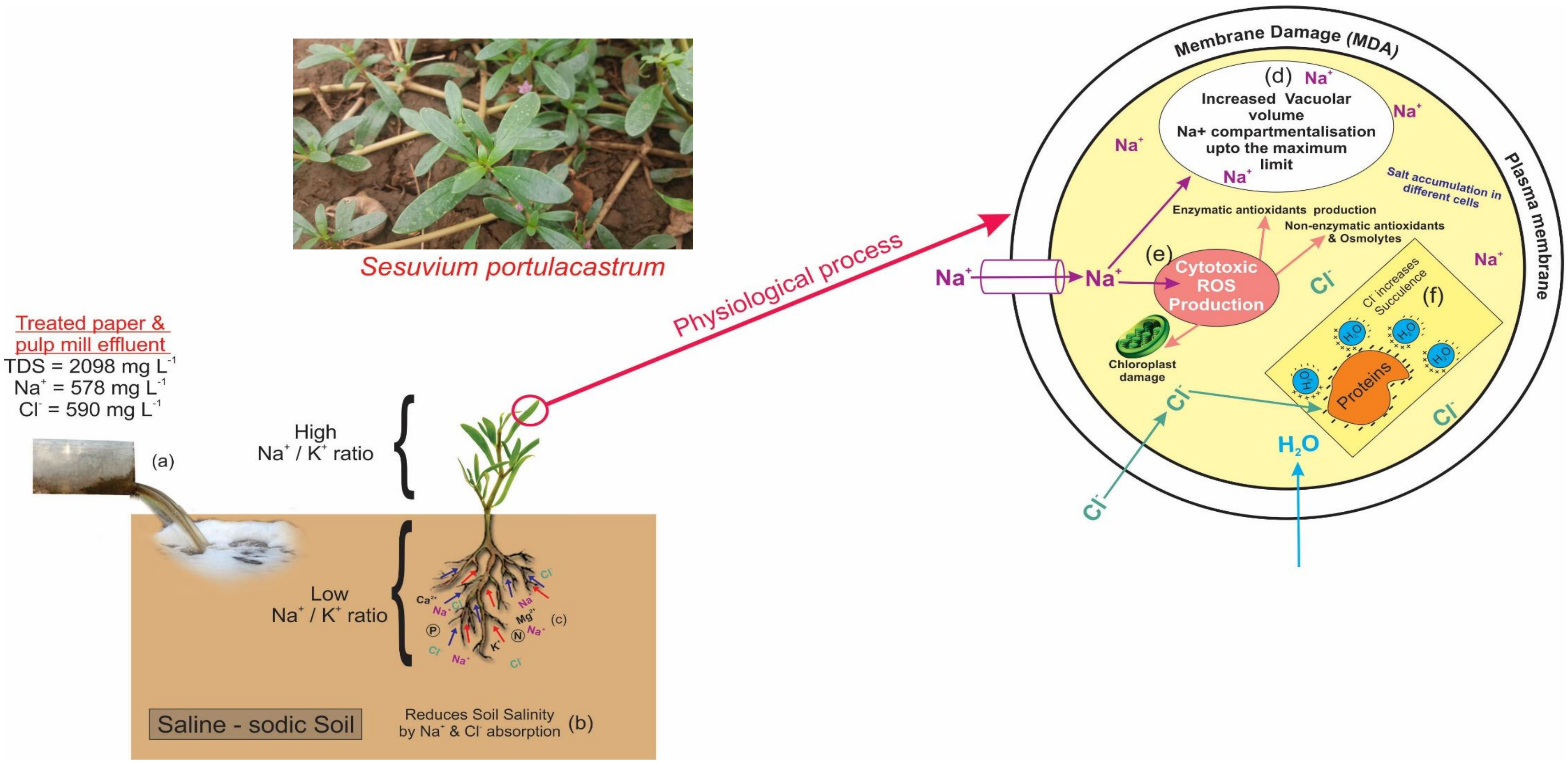


Fig.3 Schematic representing the experimental study and salt tolerance mechanism of *S. portulacastrum. S. portulacastrum* exhibits various mechanisms of salt tolerance, including physiological, biochemical, and anatomical adaptations. Salt addition leads to increased accumulation of Na^+ in the leaves. On the addition of treated pulp and paper mill effluent rich in saline and sodic ions (a), *S. portulacastrum* plant roots absorb an increased amount of sodium, chloride, and other ions (b). After sodium is accumulated in the leaves (c), the plants enhance tissue tolerance by Na^+ compartmentalisation in the vacuoles upto a certain limit (d). Excess saline stress leads to the production of ROS (e), which are balanced by the production of enzymatic antioxidants, such as catalase and SOD, and nonenzymatic osmoprotectants, such as proline, amino acids, and total sugars, which protect the membranes and enzymes. The plants also decrease the salinity by producing succulency in a chloride-rich environment (f). Overall, *S. portulacastrum* helps in the phytoremediation of salt-affected soils by removing saline salts (b)



Osmotic adjustment through the accumulation of ions and production of organic osmolytes is the main adaptive mechanism of salt stress (Zhang *et al.,* 1989).

Proline protects the structure of protein from denaturation, stabilizes the cell membrane by interacting with lipid molecules, and acts as an antioxidant (Lokhande *et al.,* 2013). The proline content was lower in the plants treated with good-quality water than in the plants treated with effluent. In the samples treated with effluent, higher proline accumulation was observed at 90 DAP than at 30 and 60 DAP. When a plant is under abiotic stress, proline accumulates and nullifies the effect of stress factors through the detoxification of ROS and protection of proteins and their structures (Slama *et al.,* 2015). A high level of proline upto 300 µmolg^{-1} leaf dry matter can be accumulated in response to stress by *S. portulacastrum* (Slama *et al.,* 2006), which indicates thekey role of proline in osmotic regulation (Lokhande *et al.,* 2010);(Moseki and Buru, 2010) for maintaining the cytoplasmic water potential (Hagibagheri and Clipson, 1986). A large amount of total sugars accumulated in *S. portulacastrum* at 30 and 60 DAP in the samples irrigated with treated paper mill effluent. The amount of total sugars decreased at 90 DAP. In the control samples, the total sugars decreased gradually after 30days. Upto 60 DAP, the total sugars may contribute to osmotic adjustment under salt stress. The osmotic adjustment decreases thereafter, which leads to increased cell damage. Studies have reported the use of sugars for complete osmotic adjustment despite the accumulation of proline (Pagter *et al.,* 2009; Lokhande *et al.,* 2010).

Influence of salinity on the chlorophyll content

Higher contents of chlorophyll a, chlorophyll b, and total chlorophyll were observed in the T_1samples than in the T_2 samples. However, the chlorophyll content decreased at 90 DAP in both the control and treated samples, which may be due to the increased salinity on the continuous addition of salt water or due to ageing**.** The process of photosynthesisis affected under salt stress. The chlorophyll pigment system is damaged, and the stomatal conductance is reduced (Shabala *et al.,* 2005). Ramani *et al.,* (Ramani *et al.,* 2006) reported that the chlorophyll a content increased at 400m MNaCl in *S. portulacastrum.*

In this study, the chlorophyll content was higher in the samples irrigated with the treated effluent (salinity stress) than in the samples treated with good-quality water (control), which indicated that the chlorophyll pigment system was unaffected under salinity stress in *S. portulacastrum* (Table 5).

Ion composition

The high sodium content in the shoots of *S. portulacastrum* is used for osmosis adjustments(Sleimi and Abdelly, 2002); (Messedi *et al.,* 2004). The sodium concentration in the leaves was 2.5–3 times higher than that in the roots and stems. *S. portulacastrum* removed 183.5 kg Na^+ ha^{-1} in 90 days, which can also be stated as the phytodesalination capacity of the halophyte. Sundararaj*et al.,*(Sundararaj *et al.,* 2014) noted that *S. portulacastrum* irrigated with primary effluent from the Pepsico industry could remove 1296 kgchlorideha^{-1} and 114 kg sodium ha^{-1} within 90 days. Ravindran *et al.,* (2007) reported that *Sesuvium* species could remove 474 kg sodium chloride ha^{-1} in 4 months.

The sodium content of the plants increased with time. The maximum concentration was noted at 90 DAP, which indicates that with increasing salinity, the sodium content increased and potassium content decreased.

Similar results were observed by Slama *et al.*, (2008) with increased Na/K under salinity stress. Although the calcium and magnesium contents are lower under salinity stress, a considerable amount is accumulated (Venkatesalu *et al.*, 1994), which indicates that the high concentration of NaCl does not affect the uptake of calcium (Messedi *et al.*, 2004). In *S. portulacastrum*, calcium accumulates in the stem and leaves as calcium oxalate crystals, which are called druces (Fig.2). The magnesium content was higher in the stem than in the leaves. Similar results were obtained by Joshi and Bhosale (Joshi and Bhosale, 1982), who stated that magnesium ions are restrained in the stem itself and only a partial amount is transported to the leaves. The ion composition in good-quality water irrigated was contributed by the initial soil, which had high salt content.

The results of the experiment in this study indicate that *S. portulacastrum* can be used for the phytodesalination of saline and saline–sodic soils even when the salinity continuously increases. Moreover, it can also be used in nonleaching conditions where the leaching of salinity with good-quality water is unfeasible. Thus, *S. portulacastrum*, which has high sodium and chloride absorption, may be a possible candidate for reducing secondary salinisation due to irrigation with sodium-rich industrial wastewater. During increased salt stress, *S. portulacastrum* adopted the following mechanism of salt tolerance(i) sodium was first accumulated in the vacuoles upto certain levels and then in the cytoplasm and protoplasm, (ii) high salt stress led to membrane damage due to high salt and ROS accumulation in the cells, (iii) osmolytes (proline and sugars) were produced for osmotic balance, (iv) Na ions beyond the vacuolar storage capacity were extruded, and (v) a larger amount of chloride anions accumulated as sodium and potassium salts with high sodium content compared to the later. Hence, *S. portulacastrum* is highly useful for the sustainable utilisation of industrial wastewater for irrigation, which is important for addressing the challenges caused by the emerging water scarcity problem worldwide.

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