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EVALUATION OF *JATROPHA CURCAS* GENOTYPES FOR REHABILITATION OF DEGRADED SODIC LANDS

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ABSTRACT

Jatropha (*Jatropha curcas* L.) is recently introduced in several states as a source of biomass and bioenergy in India. It can withstand and survive on a wide range of soils. However, information related to identification of a genotype tolerant to certain levels of sodicity is lacking. Five *Jatropha* genotypes (BTP 1-K, BTP 1-N, BTP 1-A, GCC-1, and TNM-5) collected from different ecological regions of the country were screened and evaluated for three years (2007–2010) at Lucknow, India, in sodic soils having four (20, 40, 60, and 80) exchangeable sodium percentage (ESP) levels. A large variation in plant growth, seed yield, and oil content was observed among genotypes owing to sodicity levels. Plant mortality of all the genotypes increased significantly beyond ESP of 40. Among the genotypes screened, BTP 1-A recorded the maximum plant height (240 cm), girth (34·0 cm), biomass yield ($14{\cdot}00 \pm 1{\cdot}43$ kg plant^{-1}), and number of fruits per plant (14·8) up to ESP 40. The highest seed oil content was found in BTP 1-K and BTP 1-N followed by BTP 1A and the minimum in TMN-5 and GCC-1. Soil amelioration in terms of soil pH, ESP, organic carbon, and microbial biomass was higher under genotype BTP 1-A than BTP 1-K, GCC-1, and TNM-5. Genotype BTP 1-A was found to be suitable for producing more biomass and bioenergy and rehabilitation of degraded lands. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: *Jatropha* genotypes; sodicity levels; plant growth; biomass yield; soil amelioration

INTRODUCTION

The developing world is today encountered with both economic and environmental crisis situations, and development is needed to fight against the land degradation processes (García-Orenes *et al*., 2009; Cerdà *et al*., 2010; Lemenih *et al*., 2012; Zhao *et al*., 2013; Liu *et al*., 2014; Stringer & Harris, 2014) and for production of renewable bioenergy (Pandey *et al*., 2012). Land degradation remains one of the most serious environmental problems (Singh *et al*., 2014a, 2014b), which continues to threaten the livelihoods of many people worldwide, defined as the loss of production capacity in terms of loss of soil fertility, soil biodiversity, and degradation of natural resources (Lal, 2004). It is the result of many factors, such as dryness, loss of vegetation, soil erosion, inappropriate land use, and poor management (Cerdà, 1998, 1999; Baumert *et al*., 2015; Mekonnen *et al*., 2015; Recha *et al*., 2015). An estimated $US42bn in income, and 6 million ha (mha) of productive land is lost every year owing to land degradation and declining agricultural productivity [United Nations Development Programme (UNDP)—Global Environment Facility (GEF), 2004]. Consequently, land rehabilitation is essential to reverse the trend of degradation and to improve the productivity of soils. Growing of plant species that are able to withstand water stress for revegetation in degraded landscapes are in use for long-term remediation process (Biro *et al*., 2013; Wu *et al*., 2013; Mandal & Mitrha, 2004).

About 14 mha degraded/marginal/waste lands in India have been identified for potential plantation with biofuels like Jatropha in the near future (Wani *et al*., 2009a). Most of the degraded lands are owned by resource-poor farmers and/or are the community lands used by the vulnerable groups. Biodiesel plantation to rehabilitate these lands (Singh *et al*., 2013a) constitutes a pro-poor strategy to improve their livelihoods, by providing employment and additional sources of income (Wani *et al*., 2006). Out of the total degraded lands, India is reported to have 6·73 mha salt-affected soils (Pandey *et al*., 2011). These soils are widely distributed in arid and semiarid parts of the country and pose a serious environmental threat (Singh *et al*., 2013b). These soils have high levels of soil pH (>8·5) and excess amount of soluble salts (saline) and/or exchangeable sodium (sodic), which adversely affect plant growth and yield (García-Orenes *et al*., 2009; Cerdà *et al*., 2010; Shukla *et al*., 2011; Singh *et al*., 2012a; Zhao *et al*., 2013; Liu *et al*., 2014; Stringer & Harris, 2014).

The oil imports in India are projected to reach 166 and 622 million tons by 2019 and 2047 [Tata Energy Research Institute (TERI), 2002], respectively as compared with 111 million tons of crude oil imported in 2006–2007 [Government of India (GOI), 2011]. In recent years, special emphasis is given to explore plant-based biofuels as an alternate fuel

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source or substitute of fossil fuel (Pandey *et al*., 2012). The major source of biodiesel in India can be non-edible oils obtained from plant species such as *Jatropha curcas* and *Pongamia pinnata* (Karanj). *J. curcas* Linn. (Jatropha) has recently evoked much interest worldwide as a potential biodiesel plant (Openshaw, 2000). Global attention on biofuel, environmental sustainability, and utilization of degraded lands for livelihood security with *J. curcas* has created a glorified interest in this species (Everson *et al*., 2012). It has been reported that Jatropha has potential to reclaim degraded lands sequester carbon and have high water-use efficiency (Francis *et al*., 2005; Achten *et al*., 2008; Kabir *et al*., 2009; Abhilash *et al*., 2010; Achten *et al*., 2010). Despite its several merits, Jatropha could not be cultivated yet as a potential biofuel crop, and it is considered as a semi-wild plant (Singh *et al*., 2014c). Considering the scope and challenge, the government of India has initiated National Mission on Biodiesel, giving special emphasis on cultivation of Jatropha on wastelands and under-utilized and less productive salt-affected lands to make them productive, strengthening local livelihoods, generating employment and income diversification (Mandal & Mitrha, 2004). Various accessions were evaluated under salt-affected soils and studied their growth and yield aspect (Singh *et al*., 2013c), and a single superior accession was tried in various climatic conditions in India (Singh *et al*., 2013d). From these studies, it has been observed that the establishment of Jatropha in salt-affected soils is a big concern. Therefore, the identification of a genotype able to withstand these conditions will be the most important factor to be considered (Kumar *et al*., 2008).

Much of the earlier research on Jatropha in India has focused on monitoring the production potential of locally available Jatropha genotypes and their ameliorative effect on salt-affected degraded lands, but no systematic study has been conducted to identify a highly salt-tolerant Jatropha genotype. Therefore, the present study was made to evaluate the performance of locally adapted germplasm of Jatropha in sodic soil and to identify a highly salt-tolerant Jatropha genotype. Identified salt-tolerant genotypes may be used for producing high biomass and bioenergy besides offering a sustainable amelioration of salt-affected soils. Screened genotypes will be promoted for their cultivation in degraded sodic lands and will be used for further genetic enhancement in relation to better salt tolerance.

MATERIAL AND METHODS

Biophysical Features of Study Site

A field study was carried out at Central Soil Salinity Research Institute, Regional Research Station [research farm of the Indian Council of Agricultural Research situated at sub-tropical Lucknow (80°46′32″E 26°47′45″N and 120 m above mean sea-level in Central Indo-Gangetic Alluvial Plains of India)] during 2007–2010. It occupied the concavity of gently sloping plains between 11,900- and 12,500-cm contours. The climate of the experimental site was semiarid, sub-tropical, and monsoonic receiving an average (2005–2010) annual rainfall of 817 mm. The maximum rainfall was received between 23 and 40 standard weeks (June–October) amounting to 741 mm, which was 91% of the total annual rainfall. The remaining 9% rainfall was received between 41 and 19 standard weeks (November–May). An average annual evaporation during the last 5 years was recorded as 1580 ± 81·4 mm. The evaporation rate, with increasing air temperature and atmospheric water demands, gradually increased from 1 to 22 weeks (January–June). During the rainy season at between 23 and 40 weeks (mid-June to October), evaporation rate gradually decreased following rains. Further up to 52 weeks (December), the evaporation decreased gradually owing to low temperature. The period from 23 to 40 weeks (mid-June to mid-October) remained in water surplus. The remaining period between 1–22 and 41–52 weeks remained in water deficit owing to lower rains and higher evaporation rate. The mean maximum temperature of 39 °C in the month of May and the mean minimum temperatures of 7·1 °C in the month of January indicated a seasonal climate. The mean annual temperature during the study period was recorded as 24·6 °C, whereas mean annual soil temperature was 26·5 °C. The mean summer soil temperature and the mean winter soil temperature were 31 °C and 18·0 °C, respectively. Thus, the temperature regime was hyperthermic. The moisture regime of the soils was mainly ustic.

Tube well water applied to the Jatropha plants had pH 8·2 and electrical conductivity (EC) of 63·0 $\mu S\,m^{-1}$. Among the cations, Na dominates (3·2 $mmol\,L^{-1}$) over Ca + Mg (3·5 $mmol\,L^{-1}$) followed by K (0·1 $mmol\,L^{-1}$). However, anions (carbonates + bicarbonates) dominate (6·3 $mmol\,L^{-1}$) over calcium, while sulfates were absent. The residual sodium carbonate of the water used was 2·8 $mmol\,L^{-1}$.

Initial Soil Properties of Experimental Site

The soil of the experimental site was sandy loam in texture on the surface, silty-loam and clay loam in the middle, and sandy loam in the lower layers. It is a member of fine loamy, mixed hyperthermic family of sodic Haplusteps (Sharma *et al*., 2006). The soil had physical and nutritional problems due to poor soil water cover and soil aeration caused by high bulk density (Singh *et al*., 2013e; 1·60 ± 0·05 $g\,cm^{-3}$) and poor infiltration rate (2·00 ± 0·1 $mm\,day^{-1}$). The soil was highly alkaline [pH_2 (1:2 soil : water) 9·8 ± 0·14, EC_2 242 ± 10·0 $\mu S\,m^{-1}$, and exchangeable sodium percentage (ESP) 80 ± 2·64]. The soil was poor in organic carbon (OC) content (0·80 ± 0·03 $g\,kg^{-1}$) and available N (41·96 ± 0·86 $mg\,g^{-1}$), medium in available P (11·16 ± 0·40 $mg\,g^{-1}$), and rich in available K (173·57 ± 27·71 $mg\,g^{-1}$). The gypsum requirement of the experimental soil determined by Schoonover (1952) method was 15·4 $Mg\,ha^{-1}$. The soil contained about 40-cm-thick $CaCO_3$ concretion layer in the sub-stratum (about 90 cm soil depths) inhibiting water and root penetration. The initial soil properties of the proposed experimental site are given in Table I.

Table I. Initial soil properties of the experimental site

Soil parameters	Soil depth (cm)			
	0–15	15–30	30–60	60–90
pH_2 (1:2)	9·8 ± 0·10	10·4 ± 0·10	10·3 ± 0·20	10·0 ± 0·20
EC_2 (1:2) (μS m^{-1})	242 ± 10·0	143 ± 8·0	86 ± 14·0	64 ± 7·0
ESP	80 ± 2·64	85 ± 2·64	80 ± 5·00	60 ± 5·00
OC (g kg^{-1})	0·8 ± 0·03	0·8 ± 0·03	0·6 ± 0·05	0·6 ± 0·09
Bulk density (g $cm^{-1})^3$	1·6 ± 0·05	1·5 ± 0·04	1·5 ± 0·01	1·5 ± 0·02
Available N (mg g^{-1})	41·9 ± 0·86	28·0 ± 0·33	24·3 ± 0·40	20·1 ± 0·45
Available P (mg g^{-1})	11·1 ± 0·40	9·6 ± 0·04	8·2 ± 0·51	7·6 ± 0·26
Available K (mg g^{-1})	173·5 ± 27·71	171·4 ± 26·22	143·4 ± 17·94	106·5 ± 12·16
Infiltration rate (mm day^{-1})	2·0 ± 0·1			
GR (Mg ha^{-1})	15·4 ± 0·87			

ESP = exchangeable sodium percentage; OC = organic carbon; GR = gypsum requirement; pH_2 and EC_2 = soil and water suspension ratio of 1:2.

Developing Desired Sodicity Levels

To obtain the desired sodicity levels in the experimental plots, gypsum ($CaSO_4.2H_2O$) at the rate of 15% (1·92 Mg ha^{-1}), 25% (3·85 Mg ha^{-1}), and 50% (7·7 Mg ha^{-1}) of total gypsum requirement of the field was incorporated in the month of June 2007 and mixed in 10-cm upper soil layer. However, in the control plot, no gypsum was applied and maintained as control plot. After mixing uniformly, 10 cm water was ponded for 10 days to displace (leach down) the reaction products of Ca–Na exchange down the root zone. After completion of leaching process, soil samples were collected from surface soil (0–15 cm) and analyzed to monitor the pre-planting soil status (Table II). Soil pH_2 and EC_2 were determined with digital meters (Suntes and lab-960, SI Analytics GmbH Hattenbergstr. 10 D-55122 Mainz Deutschland, Germany, Allemagne) in a 1:2 soil water suspension. ESP was estimated from exchangeable sodium ratio, and sodium adsorption ratio was drawn from the concentration values of soluble Na^+, Ca^{2+}, and Mg^{2+}. Sodium was determined through flame photometer, whereas Ca^{2+} and Mg^{2+} were determined by titration methods (Richards, 1954). The OC content was analyzed using chromic acid titration method (Wang *et al.*, 1996). Carbonate and bicarbonate were determined in soil saturation extract by titration with 0·1 N H_2SO_4, whereas chloride and sulfate were determined by silver nitrate titration (Richards, 1954). Available N was estimated by distillation of soil with $KMnO_4$ and NaOH (Subbiah & Asija, 1956). Available P and K were determined by the Olsen sodium bicarbonate extraction (Olsen & Dean, 1965) and sodium acetate extraction, respectively. The bulk density of different soil layers was determined from intact cores extracted with a core sampler of 10 cm diameter and 15 cm height (Wilde *et al.*, 1964). Microbial biomass carbon was estimated by fumigation and extraction method of Vance *et al.*, 1987. After 4 years of study, soil samples were again collected from each plot to monitor the ameliorative effect of different Jatropha genotypes on soil properties.

Collection of Jatropha Genotypes and Plantation Approach

Seedlings of five Jatropha genotypes, namely, BTP 1-K (Kanpur selection), BTP 1-N (National Botanical Research Institute, Lucknow, selection), BTP 1-A (Chindwara selection), GCC-1 (Bhavnagar selection), and TNM-5 (Tamilnadu selection) were collected from different sources and used for evaluating their tolerance to sodicity. Special emphasis was given to maintain a uniform stature of the seedlings at the time of transplanting. Nearly 6 months old seedlings of almost uniform height and collar diameter were planted at ESP 20, 40,

Table II. Soil properties after application of amendments at the time of planting of Jatropha genotypes

Soil parameters	Gypsum applied (% GR)			
	Control	15% GR	25% GR	50% GR
pH_2	9·8 ± 0·14	9·6 ± 0·13	9·2 ± 0·21	8·9 ± 0·28
EC_2 (μS m^{-1})	242 ± 10	30 ± 6·0	50 ± 2·0	35 ± 2·0
ESP	80·0 ± 2·21	60 ± 1·24	40·0 ± 2·00	20·0 ± 2·30
OC (g kg^{-1})	0·8 ± 0·02	1·1 ± 0·10	1·2 ± 0·09	1·3 ± 0·04
Ca^+ Mg (C mol kg^{-1})	2·1 ± 0·11	2·6 ± 0·21	1·6 ± 0·08	1·6 ± 0·04
CO_3 (C mol kg^{-1})	0·0 ± 0·00	1·0 ± 0·17	3·0 ± 0·26	2·0 ± 0·36
HCO_3 (C mol kg^{-1})	12·5 ± 0·70	12·5 ± 0·5	10·5 ± 0·50	4·5 ± 0·70
Cl (C mol kg^{-1})	2·0 ± 0·35	2·0 ± 0·12	3·0 ± 0·17	2·0 ± 0·10
SO_4 (C mol kg^{-1})	0·0 ± 0·00	0·0 ± 0·00	0·0 ± 0·00	0·0 ± 0·00
Available N (mg kg^{-1})	41·9 ± 0·45	43·2 ± 0·33	43·1 ± 0·40	43·7 ± 0·86
Available P (mg kg^{-1})	7·5 ± 0·26	8·2 ± 0·51	9·6 ± 0·04	11·2 ± 0·40
Available K (mg kg^{-1})	173·5 ± 27·71	175·9 ± 26·22	179·2 ± 17·94	186·8 ± 12·16
Bulk density (g cm^{-3})	1·6 ± 0·05	1·6 ± 0·04	1·5 ± 0·01	1·5 ± 0·02

ESP = exchangeable sodium percentage; OC = organic carbon; GR = gypsum requirement; pH_2 and EC_2 = soil and water suspension ratio of 1:2.

60, and 80 (control) in a split-plot design with four replications at a spacing of 3 m × 2 m (row to row and plant to plant) in March 2007. Four plants of each genotype covering a 24-m^2 area were planted in each replication. For proper establishment of the seedlings, three irrigations of good quality water were given at monthly interval with 10-cm depth of water during the first year of planting (2007), and after that, one irrigation in the month of June when the temperature was more than 40 °C was applied annually. No fertilizer was applied to the plants during the study period.

Growth and Biomass

The observation on physical parameters, that is, survival of plants (%), plant height, plant girth (60 cm from the ground surface), number of branches (primary and secondary), crown diameter, and number of leaves per plant were recorded from each treatments every year. Flowering, fruiting, and seeding traits were monitored in the third year at the end of the experiment. The ripening of the fruits was not at the same time; therefore, fruits were harvested at weekly interval. To measure the biomass yields, three representative plants of each genotype from each treatment were uprooted. The roots and shoots were separated and air-dried to measure air dry biomass. The roots were exposed through water pressure, and numbers of primary, secondary, and tertiary roots were counted. Root length was measured using a measuring tape. Litter collectors of 100 cm × 100 cm size, with 0·5-mm mesh steel net, were used to measure the litter fall yield annually and measured total litter fall added to the soils during 3 years of study. Wood density was measured from the mass/volume relationship from the stem removed from the diameter at breast height (130 cm) as described by Achten *et al*. (2010).

Seed Morphology

One hundred air-dried fruits were collected randomly from each treatment to measure 100 fruit weight. Kernels were removed from the fruits manually and measured 100 kernel weights. Further, seeds along with kernel were drawn randomly and measured separately. Seed length and thickness were measured with an electronic Vernier caliper. The chlorophyll content was calculated according to the estimation carried out by Arnon (1949). The oil content of different genotypes was extracted using a Soxhlet apparatus. The oil was extracted from the samples with the help of petroleum ether followed by continuous distilling for 4 h. The oil was recovered by complete distilling of most of the solvent on a heating metal. The oil was then transferred to a measuring cylinder. The measuring cylinder is then placed over water bath for complete evaporation of solvent for about 2–3 h, and volume of oil was recorded and expressed as oil content (%) as follows:

$$\text{Oil content } (\%) = (\text{Oil weight}/\text{Sample weight}) \times 100$$

Statistical Analysis

Data for various growth parameters and yield-related traits were subjected to statistical analysis as per the standard analysis of variance technique using AGRES Statistical Software version 3·01. The treatment comparisons were made using *t*-test at a 5% level of significance.

RESULTS AND DISCUSSION

Effect of Sodicity Levels on Survival and Growth

During the initial 3 months of planting, the survival percent of all the genotypes at all the sodicity levels was quite satisfactory, and no mortality was recorded. After 3 months, mortality was observed in some of the genotypes at sodicity of ESP 60 and 80, and it increased with time. At 6 months of age, the lowest survival (47·4%) was recorded with genotype GCC-1 at ESP 80. After 12 months of planting, survival percent of all the genotypes beyond ESP 40 reduced significantly. The highest mortality at this stage was recorded in genotype GCC-1 followed by TNM-5, BTP 1-A, BTP 1-K, and BTP 1-N. Survival percent reduced with every level of sodicity with increasing time. The highest reduction in this parameter was recorded at ESP 80 where mortality in all the genotypes was about 50% or more. Mortality in all the genotypes was recorded even after 24 months of planting and continued up to 36 months of plant age, but the difference in survival percent between the age of 24 and 36 months was not significant. Poor survival indicated their inability to tolerate high sodicity and harsh soil conditions (Paria & Dass, 2005). Among the genotypes, BTP 1-N reported the highest survival percent over the period of 3 years followed by BTP 1-A and BTP 1-K (Figure 1 and 3).

The data pertaining to agronomical observations revealed that the plant height and girth decreased significantly with increasing levels of sodicity. The maximum plant height (2·13 m) and girth (30·66 cm) were recorded at ESP 20, whereas the minimum at ESP 80 (Figure 2). Poor growth at ESP 80 may be attributed to high sodicity stress and nutrient deficiency, that is, lack of available N and P. Reduction in plant growth due to salt stress has also been reported in several other plant species (Jaleel *et al*., 2007). It could have been due to reduction of the photosynthesizing leaf area, high pH, and ion imbalance around the rhizosphere caused by alkaline salt stress (Shi *et al*., 1998). Plant height (1·17 to 2·02 m) varied significantly among different genotypes. Genotype BTP 1-A attained the maximum plant height and the minimum with GCC-1. However, the maximum plant girth was recorded with genotype BTP 1-K and the minimum with GCC-1. Canopy spread varied widely from 66·63 to 92·55 cm among different genotypes with the maximum in BTP 1-A and the minimum in GCC-1. Genotypes BTP 1-K, BTP 1-N, and BTP 1-A attained significantly higher canopy cover over GCC-1 and TNM-5 (Figure 2C).

Effect of Sodicity Levels on Root and Shoot Development

The root and shoot development of Jatropha is severely affected under sodic soils. Increasing levels of sodicity significantly decreased the number of branches and root length. Jatropha genotypes planted at ESP 20, 40, and 60 produced 82·60%, 39·13%, and 13·04% more number of primary and

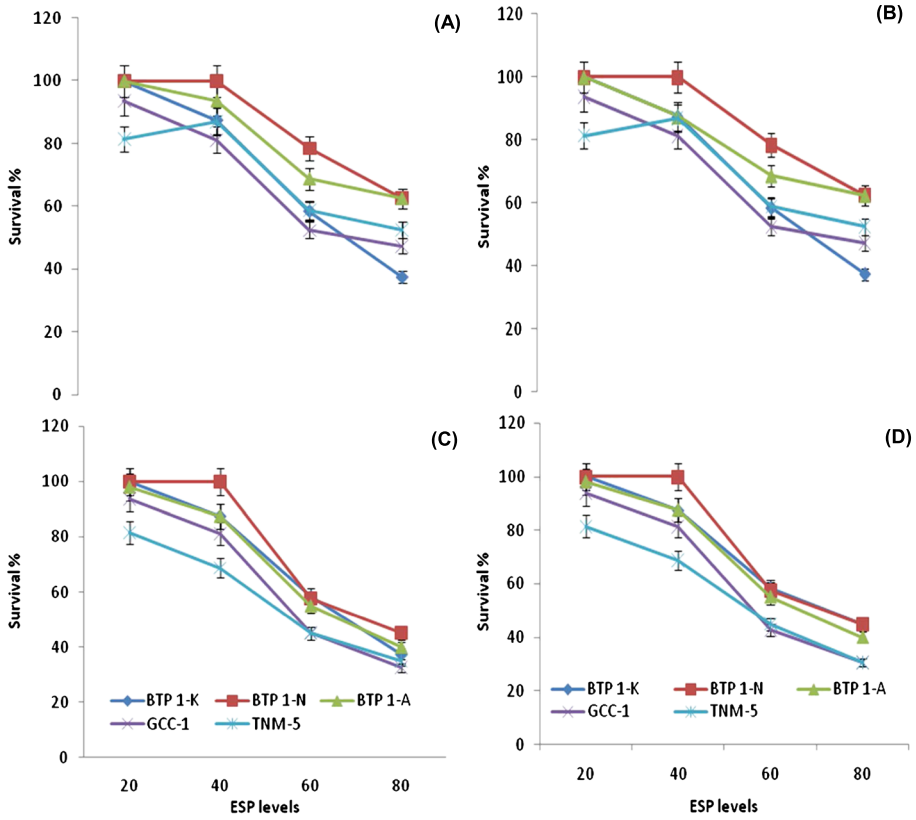

Figure 1. Survival percent of Jatropha genotypes (A) 6 months after planting, (B) 12 months after planting, (C) 24 months after planting, and (D) 36 months after planting. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

107·01%, 101·75%, and 49·12% secondary branches over the ESP 80 (Table III). Similarly, root length of primary, secondary, and tertiary roots at ESP 20, 40, and 60 was higher over ESP 80. It may be because of sodic soils having less water available for crops due to high salt concentration in the soil solution. It is evident from various research

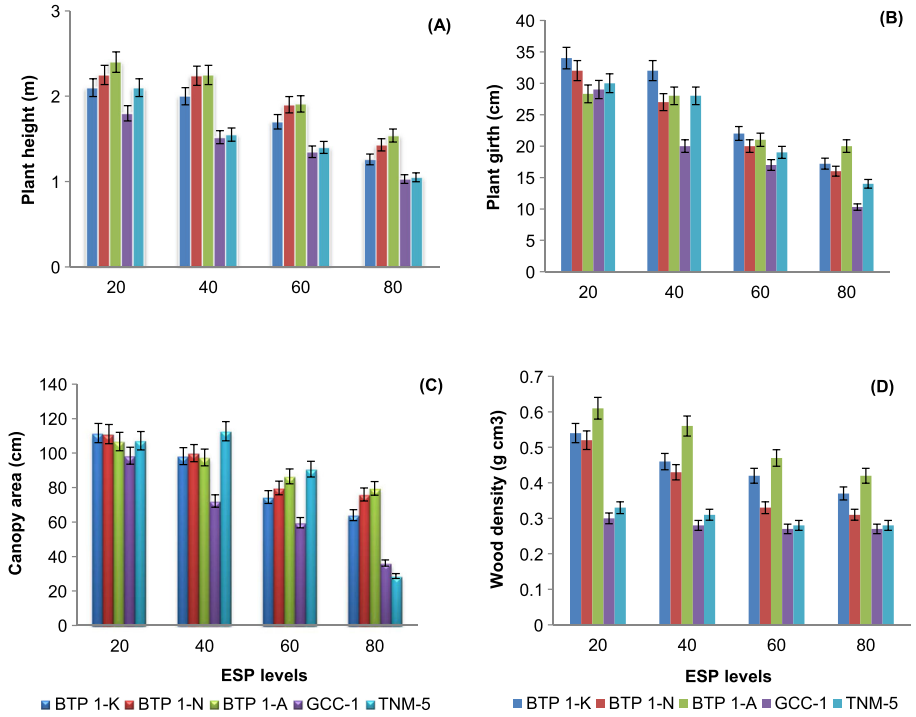

Figure 2. (A) Plant height (cm), (B) plant girth (cm), (C) canopy area (cm), and (D) wood density (g cm^{-3}) of five Jatropha genotypes under different sodicity levels (significant differences in plant height, plant girth, canopy area, and wood density are at the 5% level of significance). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table III. Number of branches and root growth parameters of Jatropha genotypes under different sodicity levels

Treatments	Number of primary branches	Number of secondary branches	Root length (cm)	Number of primary roots	Number of secondary roots	Number of tertiary roots
Genotypes						
BTP 1-K	6	14	22·10	11	26	57
BTP 1-N	8	10	25·13	10	27	44
BTP 1-A	6	15	30·43	13	34	112
GCC-1	4	9	15·75	6	18	38
TNM-5	5	7	13·95	8	22	41
LSD ($p = 0·05$)	1·52	3·55	5·47	4·09	4·21	9·36
Sodicity levels (ESP)						
20	8	19	18·52	19	38	92
40	6	11	27·86	10	27	65
60	5	8	20·98	7	21	45
80	5	6	18·52	6	16	32
LSD ($p = 0·05$)	1·14	3·55	5·66	4	4·21	9·36

LSD = least significant differences; ESP = exchangeable sodium percentage.

reports (Ray & Khaddar, 1995) that, owing to change in soil redox conditions, pH, and concentrations of toxic ions such as Na^+ and HCO_3^-, soil sodicity becomes adverse to root development and function (Wright & Rajpar, 2000; Rajpar & Wright, 2000). Marked differences in genotypic variability were observed in terms of number of branches, root

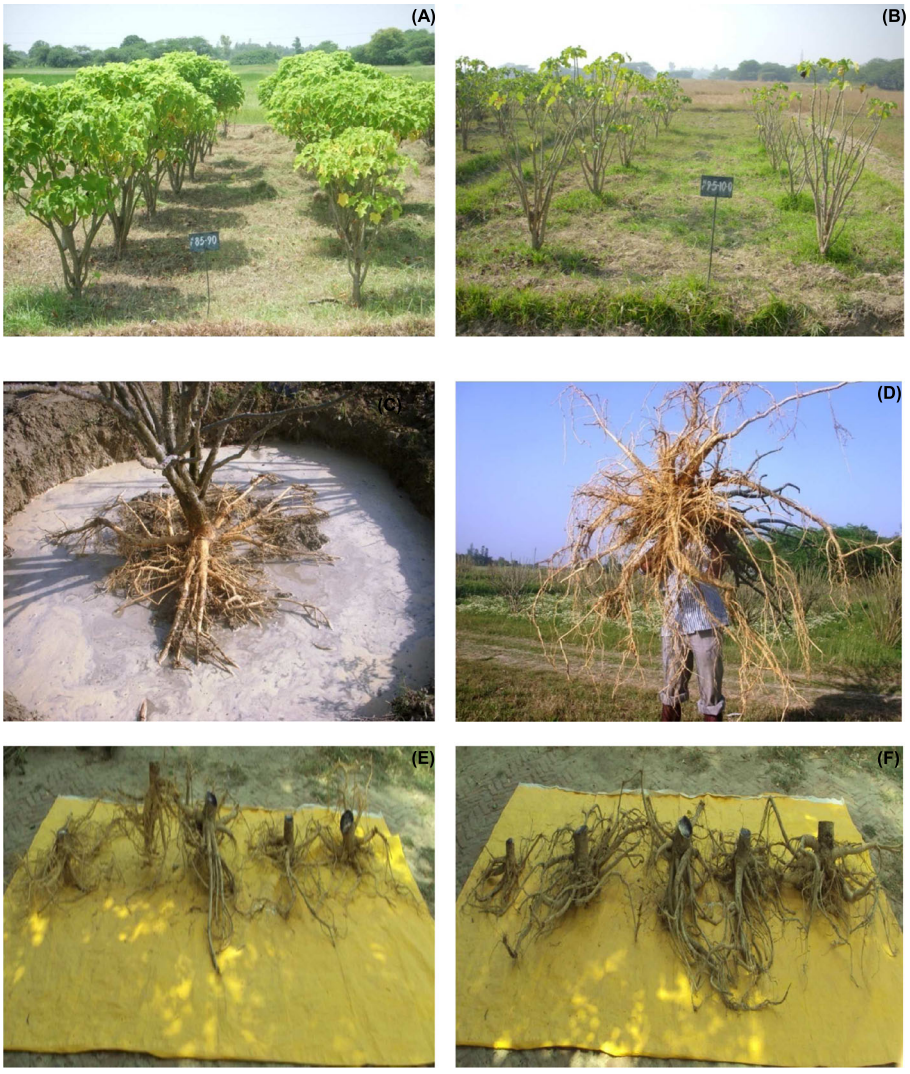

Figure 3. (A) Jatropha growth at ESP 20, (B) Jatropha growth under control (ESP 80), (C) root development pattern, (D) root length and spread, and (E and F) root biomass of five genotypes at different sodicity levels.

length, and number of roots. The maximum number of primary and secondary branches was recorded in genotype BTP 1-N, whereas the minimum in genotype GCC-1. Root growth in terms of root length and number of primary, secondary, and tertiary roots was significantly higher in BTP 1-A over BTP 1-K, BTP 1-N, GCC-1, and TNM-5 (Figure 3).

Effect of Sodicity Levels on Biomass Yield

The response of Jatropha seedlings to increasing ESP levels in terms of total biomass (root + shoot) was observed. The highest total biomass was recorded with genotype BTP 1-A and the minimum with GCC-1. There was no significant difference in root biomass between the genotypes. However, a significant difference in shoot biomass between the genotypes was recorded. Genotype BTP 1-A produced the maximum roots and shoot biomass. Total biomass in genotypes BTP 1-A, BTP 1-N, and BTP 1-K was statistically at par but significantly higher over genotypes GCC-1 and TNM-5. Total biomass of BTP 1-K, BTP 1-N, BTP 1-A, and TNM-5 was 140·8%, 116·3%, 185·7% and 63·3% higher than GCC-1, respectively. Levels of sodicity significantly responded to the total biomass yield of Jatropha. Jatropha genotypes grown at ESP 20, 40, and 60 had 542·85%, 323·12%, and 159·18% higher total biomass yields over ESP 80. The shoot biomass was almost double than the root biomass at all the sodicity levels (Table IV). A significant interaction between genotypes and sodicity levels on biomass yield was also recorded. The interaction given in Table V revealed that genotype BTP 1-A produced the maximum biomass (2·5 t ha^{-1}) at ESP 20, whereas the minimum (0·29 t ha^{-1}) at untreated control (ESP 80). As the level of sodicity increased from ESP of 20 to 40, 40 to 60, and 60 to 80, the total biomass yield of all the genotypes reduced significantly. The biomass yield at ESP 20 was 47·86%, 168·7%, and 603·25% higher over ESP 40, 60, and 80, respectively. A significant reduction in this character was recorded when the sodicity level increased above ESP 40.

Table IV. Biomass yield of five Jatropha genotypes under different sodicity levels 36 months after planting

Treatments	Total biomass (root + shoot) (kg plant^{-1})	Root biomass (kg plant^{-1})	Shoot biomass (kg plant^{-1})
Genotypes			
BTP 1-K	11·8 ± 1·20	3·1 ± 0·20	8·7 ± 0·26
BTP 1-N	10·6 ± 1·05	2·7 ± 0·31	7·9 ± 0·24
BTP 1-A	14·0 ± 1·43	4·3 ± 0·24	9·6 ± 0·30
GCC-1	4·9 ± 0·74	2·0 ± 0·15	2·9 ± 0·17
TNM-5	8·0 ± 0·65	2·9 ± 0·14	5·1 ± 0·15
LSD (p = 0·05)	4·66	2·26	2·40
Sodicity levels (ESP)			
20	18·9 ± 1·10	5·4 ± 0·34	13·5 ± 0·24
40	12·4 ± 1·12	4·0 ± 0·28	8·5 ± 0·20
60	7·6 ± 65	2·3 ± 0·18	5·3 ± 0·14
80	2·9 ± 0·35	0·4 ± 0·14	2·5 ± 0·16
LSD (p = 0·05)	1·41	1·86	1·63

LSD = least significant differences; ESP = exchangeable sodium percentage.

Table V. Interaction effect of genotypes and sodicity levels on biomass yield (Mg ha^{-1})

Genotypes	Sodicity levels (ESP) 20	40	60	80	Means for genotypes (G) LSD (p = 5) = 2·46
BTP 1-K	2·30	0·84	0·65	0·33	1·03
BTP 1-N	1·65	1·28	0·86	0·40	1·04
BTP 1-A	2·50	1·98	1·01	0·29	1·44
GCC-1	0·80	0·50	0·30	0·07	0·41
TNM-5	1·40	1·25	0·41	0·14	0·80
Means for sodicity levels (S)	1·73	1·17	0·64	0·24	
LSD (p = 05) = 1·41					
LSD (p = 05) for interaction G × S = 3·68					

LSD = least significant differences; ESP = exchangeable sodium percentage

Pandey *et al*. (2012) reported higher biofuel yield from *J. curcas* at lower sodicity levels. Wood density of different genotypes varied from 0·27 to 0·61 g cm^{-3} (Figure 2D). Genotypes grown at ESP 20 and 40 recorded the maximum wood density, and it reduced significantly with increasing level of sodicity.

Effect of Sodicity Levels on Fruit Yield

Days to flowering is an important parameter to evaluate the stress tolerance level of any genotype. Among the genotypes evaluated, genotypes BTP 1-K, BTP 1-N, and BTP 1-A start flowering after 30 months of planting; however, genotypes GCC-1 and TNM-5 started flowering 36 months after planting (Table VI). Genotype BTP 1-A started flowering about 46 and 62 days earlier than genotypes BTP 1-K and BTP 1-N, respectively. The response of Jatropha genotypes to increased sodicity levels remains negative. Early flowering was recorded at lower sodicity levels (ESP 20 and 40). There was no significant difference in days to flowering between ESP 20 and 40, whereas at ESP 60 and 80, flowering was delayed significantly, or there was no flowering in some of the genotypes. Genotype BTP 1-A produced significantly higher numbers of fruit-bearing branches over BTP 1-K, BTP 1-N, GCC-1, and TNM-5. The number of fruit-bearing branches significantly reduced with increasing levels of sodicity. The maximum number of fruit-bearing branches (5·2 plant^{-1}) was recorded at ESP 20 and the minimum (0·9 plant^{-1}) at ESP 80. The reduction in fruit-bearing branches with ESP 20–40, 40–60, and 60–80 was recorded to be 26·8%, 70·8%, and 366·6%, respectively. The maximum number of fruits per plant was recorded with genotype BTP 1-A and the minimum with GCC-1 and TNM-5 at ESP 80. A significant difference in this parameter was recorded in all the genotypes except GCC-1 and TNM-5. Data from various earlier reports indicated that seed yield of *J. curcas* varies from 0·2 to more than 2·0 kg plant^{-1} (Jongschaap *et al*., 2007; Tewari, 2007; Achten *et al*., 2008; Jones & Miller, 1992). Increasing levels of sodicity significantly decreased the number of fruits per plant. The magnitude of reduction in fruits per plant was higher at ESP 60 and 80. One hundred fruit weight of genotype BTP 1-N was significantly

Table VI. Days to flowering, fruit yield, and contributing characters of Jatropha genotypes under different sodicity levels

Treatments	Days to flowering	Fruit-bearing branches plant^{-1}	No. of fruits plant^{-1}	100 fruit weight (g)	100 kernel weight (g)	Chlorophyll content in leaf (mg L^{-1})
Genotypes						
BTP 1-K	946·25	4	11	209·52	71·70	0·92
BTP 1-N	962·50	3	9	219·92	74·91	1·01
BTP 1-A	900·00	5	15	199·51	68·42	1·12
GCC-1	1112·50	2	8	209·10	71·41	1·02
TNM-5	1097·50	2	7	138·41	52·33	1·11
LSD ($p = 0·05$)	23·10	1·95	0·61	2·62	3·15	NS
Sodicity levels (ESP)						
20	965·00	5	19	278·70	94·40	1·32
40	980·00	4	13	198·91	68·42	1·12
60	998·40	2	7	167·22	57·91	0·91
80	1070·00	1	2	136·23	50·24	0·73
LSD ($p = 0·05$)	18·10	0·81	0·96	3·50	1·56	0·002

LSD = least significant differences; ESP = exchangeable sodium percentage.

Table VII. Seed morphological characters and oil content of Jatropha genotypes under different sodicity levels

Treatments	100 seed weight with seed coat (g)	100 seed weight without seed coat (g)	100 seed coat weight (g)	Seed length (mm)	Seed thickness (mm)	Oil content (%)
Genotypes						
BTP 1-K	137·83	80·03	57·80	16·43	8·38	37·50
BTP 1-N	145·00	83·05	61·95	16·73	8·60	37·20
BTP 1-A	131·10	72·40	58·70	16·68	8·95	37·50
GCC-1	137·70	84·52	53·18	15·83	8·85	27·60
TNM-5	86·10	48·57	37·53	15·28	7·50	32·30
LSD ($p = 0·05$)	1·88	3·58	2·30	0·42	0·43	0·32
Sodicity levels (ESP)						
20	184·30	111·84	72·46	17·58	13·14	37·50
40	130·50	69·40	61·10	16·72	9·64	37·00
60	109·30	54·96	48·34	15·86	6·26	35·00
80	86·00	52·58	33·42	14·58	4·78	33·00
LSD ($p = 0·05$)	2·65	1·82	0·88	0·51	0·37	0·41

LSD = least significant differences; ESP = exchangeable sodium percentage.

higher over the rest of the genotypes (Table VI). A significant difference in 100 fruit weight between the sodicity levels was also recorded. A similar trend was observed in 100 kernel weights. Stability of chlorophyll content is an important parameter to discriminate genotypes for stress tolerance. The maximum chlorophyll content was recorded in the leaves of genotypes BTP 1-A and TNM-5, whereas the minimum in BTP 1-K (Table VI). There was no significant difference in chlorophyll content between the genotypes. However, a significant difference in this character was recorded with level of sodicity. The maximum chlorophyll content was recorded at ESP 20, and it reduced with increasing level of sodicity. These results are in accordance with Sahai *et al.* (1983) and Reddy & Vora (1986).

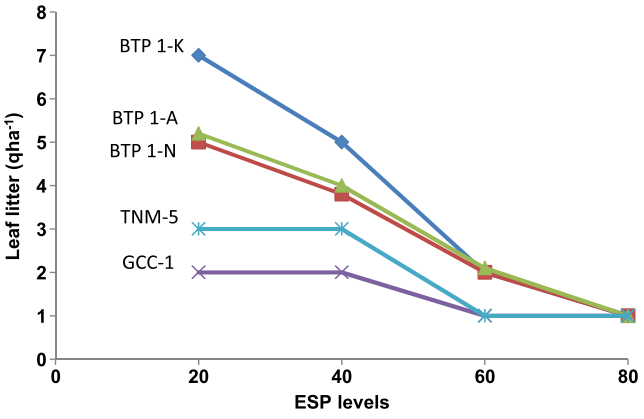

Figure 4. Total litter mass added to the soil during 3 years through different genotypes under different sodicity levels. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Effect of Sodicity Levels on Seed Morphology and Oil Content

Seed morphological characters like seed weight, seed length, and seed thickness varied between the genotypes and are affected with levels of sodicity. Genotype BTP 1-N was significantly superior in most of the seed morphological characters like 100 seed weight with and without seed coat, 100 seed coat weight, and seed length except seed thickness (Table VII). Increasing the level of sodicity significantly

Table VIII. Changes in soil properties (0–15 cm) soil depth under different Jatropha genotypes 36 months after planting

Treatments	pH_2	EC_2	ESP	OC ($g\,kg^{-1}$)	CO_3 ($me\,L^{-1}$)	HCO_3 ($me\,L^{-1}$)	Bd ($g\,cm^{-1}$)	MBC ($\mu g\,g^{-1}$)
Genotypes								
BTP 1-K	9·06	0·46	31·28	1·89	0·00	4·50	1·45	78·60
BTP 1-N	9·10	0·62	30·00	1·87	0·00	6·50	1·47	78·91
BTP 1-A	8·95	0·53	28·50	1·92	0·00	5·50	1·42	86·50
GCC-1	9·21	0·63	31·00	1·72	1·00	7·00	1·53	58·41
TNM-5	9·18	0·60	32·45	1·61	1·00	7·50	1·50	63·52
Sodicity levels (ESP)								
20	8·73	0·46	20·74	2·51	0·00	4·50	1·35	90·01
40	8·86	0·52	27·18	2·03	1·00	6·50	1·38	86·21
60	9·27	0·52	33·02	1·48	0·00	10·00	1·42	58·62
80	9·53	0·77	41·64	1·19	2·00	10·50	1·53	42·63

EC = electrical conductivity; ESP = exchangeable sodium percentage; OC = organic carbon; Bd = bulk density; MBC = microbial biomass carbon; pH_2 and EC_2 = soil and water suspension ratio of 1:2.

decreased the seed morphological characters. Genotypes grown at ESP 20 and 40 showed significantly better seed morphological characters than ESP 60 and ESP 80 because an increase in salt concentration produced a stressful effect on flowering and fruit formation (Khan *et al*., 1995). The maximum oil content was recorded in genotypes BTP 1-K and BTP 1-A and the minimum in GCC-1 and TNM-5. Among the treatment combinations, the maximum oil yield was recorded in genotypes BTP 1-K and BTP 1-A at ESP 20. However, all the treatment combinations registered significantly lower oil content (Table VII).

Effect of Genotypes on Soil Physicochemical Properties

The effect of Jatropha genotypes on physicochemical properties of sodic soil was observed after 3 years of plantation. It was observed that the plantation of *J. curcas* on sodic soils improved the soil physicochemical properties. The degree of improvement was linked to the annual litter fall, total biomass production, root development, and the level of management practices. The maximum litter fall during the period of 3 years of study was recorded under genotype BTP 1-A followed by BTP 1-K. When the level of sodicity increased from ESP of 20–40, 40–60, and 60–80, the litter fall yield of genotypes BTP 1-K, BTP 1-N, and BTP 1- A reduced significantly. However, there was no significant reduction in this parameter between genotypes GCC-1 and TNM-5 (Figure 4). The winter months accounted for total litter fall that was composed of about 100% foliage. The maximum soil improvement in terms of reduction in soil pH, EC, ESP, and buildup of OC in soil was recorded with genotype BTP 1-A and the minimum with TNM-5. This is in agreement with earlier studies (Qadir *et al*., 2002; Singh *et al*., 2012a, 2012b; Tripathi & Singh, 2005). The organic matter added through leaf litter and root decomposition produces organic acids that reduce soil pH. Root exudates also play an important role in reducing soil pH (Jamaluddin & Shukla, 2012). The reduction in ESP due to different genotypes may be due to increased availability of Ca^{++}. The nitrogen and phosphorus contents in the soil improved considerably owing to addition of organic matter through litter fall and root exudates (Singh *et al*., 2013b). Moreover, the decomposition of litter leads to evolution of CO_2, which helps mobilize the inherent Ca. The released Ca can hasten the reclamation by replacing the exchangeable Na from the soil, thus reducing the soil sodicity and pH levels (Singh *et al*., 2013d). Data revealed that the OC content of the surface soil (0–15 cm) increased to 92·30%, 69·16%, 87·22%, and 32·22% higher over the initial value (Table VIII). Sodic soils generally have high bulk density, which inhibits water movement and leaching of salt from the surface (Singh *et al*., 2012b). The root system of the Jatropha genotypes evaluated is shallow, which enhances the proportion of macropores to micropores, which lowered the bulk density. Bulk density of the surface soil decreased at higher rate where the Jatropha is planted at lower ESP. In addition, soil microbial biomass carbon has increased after 3 years of Jatropha plantation. Plantations of *J. curcas* on degraded lands are supposed to offset the degraded soil properties at varying extents corresponding to their growth and age (Kaushik *et al*., 2007; Abhilash *et al*., 2010; Garg *et al*., 2011). *J. curcas* is also known to improve the structural stability, and carbon and nitrogen contents of degraded Entisol of India (Ogunwole *et al*., 2007; Ogunwole *et al*., 2008).

CONCLUSIONS

The study concludes that based on survival, superior growth, biomass production, seed morphological characters, seed yield and contributing characters, oil content, and soil amelioration, the Jatropha genotype BTP 1-A is found to be highly suitable for rehabilitation of sodic lands. It is recommended that this genotype can perform well in sodic soils having ESP of up to 40. It can produce a reasonable good oil yield within a short period of time with minimum inputs. Therefore, it is advisable that this seed source should be used for plantation in partially reclaimed sodic soils to harness the maximum productivity as well as economic return from such degraded lands. Identification of salt-tolerant genotype will help in identifying sound genetic base as donor genotype for salt-tolerance studies in *J. curcas*.

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