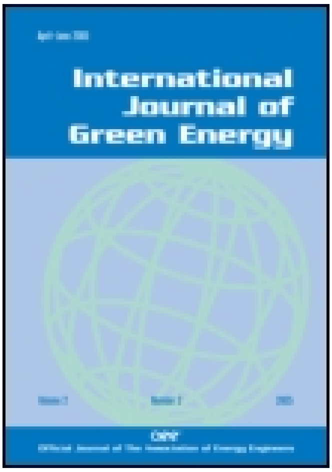

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THE FIELD PERFORMANCE OF SOME ACCESSIONS OF *JATROPHA CURCAS* L. (BIODIESEL PLANT) ON DEGRADED SODIC LAND IN NORTH INDIA

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Twenty four accessions of* Jatropha curcas *L. (JCL) were planted on a degraded sodic land in Lucknow, India, in which growth and yield traits were measured over five years (2006–2010). There was a large variation in growth and yield among these accessions, and the average seed yield (118 g plant^{-1}) and oil content (30%) of JCL on the sodic land were sufficiently low to make it an economically feasible venture for biofuel production. The seed:fruit, kernel:seed ratios and the 100 seed test weight were also measured. In order to make it an economically viable proposition, some preliminary screening were done to assort the superior accessions (CSMCRI-C1, NBPGR-Urlikanchan, NBPGR-Chhatrapati, and NBPGR-Hansraj), on the basis of growth and yield traits, that have attained an average height of 264.6–344.6 cm, with an 8.5- to 10-cm collar diameter, 41–57 branches per plant, a 209- to 290-cm canopy spread, a 178–246 g plant^{-1} seed yield, and a 27–38% oil content at five years. Though they do not correlate well between growth/yield and gas exchange parameters (photosynthetic rate, transpiration, stomatal conductance, and water use efficiency), even then these markers are useful to screen out a large number of accessions at an early stage before the yield starts or stabilizes to increase the land use efficiency. The changes in soil properties after five years of the plantations showed reduction in soil pH and electrical conductivity, with a parallel increase in organic carbon, organic nitrogen, microbial biomass, and dehydrogenase activity, indicating that JCL had a modest ability to reclaim the sodic soils.*

Keywords: *Biodiesel production; Oil content; Seed yield; Wasteland utilization; Energy crop*

INTRODUCTION

In recent years, *Jatropha curcas* L. (JCL) has been introduced in several states of India on a wide scale to promote the biodiesel program of the country. The government of India made a target to develop 4 lakh hectares (ha) of land under *Jatropha* plantation during five years under a national mission of biodiesel (Government of India 2003). As a

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consequence, its plantations were done on wastelands on a large scale in the past few years. *Jatropha curcas* is known to reclaim degraded lands, with a potentially positive impact on biodiversity and soil resources through building of soil organic matter, and its root symmetry controls soil erosion (Francis, Edinger, and Becker 2005; Achten et al. 2008; Kabir, Hussain, and Kim 2009; Abhilash et al. 2010; Achten et al. 2010a, 2010b). JCL has great potential for sustainable environmental development (Pandey et al. 2012). Elite planting material is being looked for such plantations for ensuring competitive returns compared with other plantation crops. Because its scope as a commercial energy crop in the country has not been well explored till date; thus, as a consequence, questions have been raised about the Indian biofuel policy (Rajgopal 2008). Besides its several merits, it could not be domesticated yet as a potential oil crop and it is still considered as a wild plant. Considering the scope and the threat, a major research project was conceived by the Council of Scientific and Industrial Researches (CSIR) during 2005 under the New Millennium Indian Technology Leadership Initiative (NMITLI) program to evaluate the field performance of various accessions of JCL on different degraded lands (CSIR 2006). Sodic land is one of them, where we raised the plantations of some accessions and studied growth and yield aspects for five years.

In India, total wastelands are estimated to be 63.85 million ha (ICAR 2010). Among these, saline (21,989 ha) and sodic (1,346,971 ha) soils occupy about 1.35 million ha alone in the state of Uttar Pradesh (Sharma, Rao, and Saxena 2004). These soils with excess amount of soluble salts (saline) and/or exchangeable sodium (sodic) adversely affect crop/vegetation growth and yield (Shukla et al. 2011; Singh et al. 2012a). Sodic soils are being reclaimed now and used under the agriculture and forestry sector with government support as the owners of such land (small and marginal farmers) cannot afford the reclamation expenditures (Singh, Singh, and Singh 2012a,b). Pandey et al. (2011) proposed a need of new approaches for sustainable development of these lands under diverse land use systems. It is expected that JCL may find a suitable place for growing on such unproductive lands with limited water and nutrient requirements, as arable land would not be available for energy plants considering the country's food security. Some accessions (24) of JCL were planted five years back on a degraded sodic land mainly to observe its production potential over the years (2006–2010), for which large expectations have been speculated in the light of past reports (Jones and Miller 1992; Francis, Edinger, and Becker 2005). The soil reclamation effect was also observed simultaneously. The main objective of the study was to find out superior accessions of JCL for degraded sodic lands in terms of growth, yield, and oil percentage that could be economically exploited on such lands. It is expected that unless a plant produces a reasonable amount of seed annually after five years of growth, it cannot be sustainable for biofuel industry to cater the needs of at least 5% blending by 2012 as targeted in the Indian biofuel policy.

MATERIAL AND METHODS

Experimental Site

The study was carried out at the Banthra Research Station of the CSIR-National Botanical Research Institute, Lucknow (26º42'N 80º49'E), India, during 2005–2010 (Figure 1). Six-month-old rooted cuttings of some accessions, acquired from different biogeographic regions of India, were planted on the experimental site. The meteorological data on temperature, rainfall, and relative humidity during this period were obtained

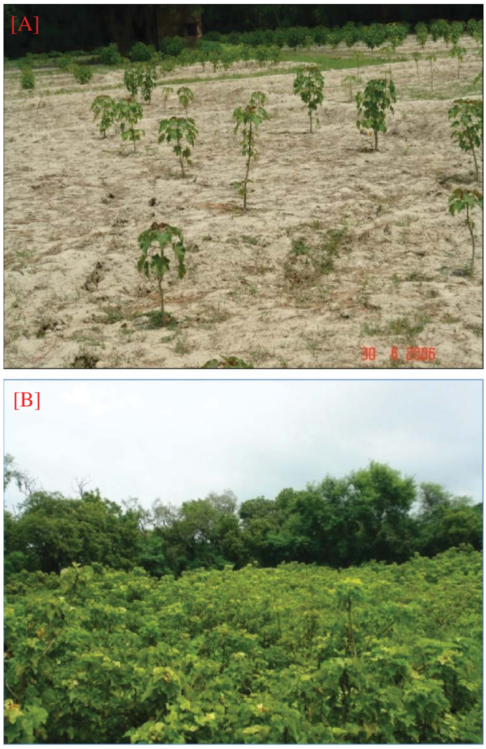

Figure 1 Initial plantation of *Jatropha curcas* L. on sodic land (A), an overview of plantation after five years of growth (B) (color figure available online).

from the Indian Meteorology Department (IMD), Amausi, Lucknow (5 km away from the experimental site). An average annual rainfall during these five years is measured as 789.4 ± 100 mm, the minimum-maximum temperature varied from 19.2 ± 1.08°C to 32.1 ± 0.16°C, and the average annual relative humidity was recorded as 60.7 ± 2.01%. The soil of the experimental site was a representative of the degraded sodic land commonly found in large tracts in north India. It is known for holding a high soil pH (>9), poor organic carbon and nitrogen contents, crusting and hard setting properties due to high bulk density and exchangeable sodium percentage (ESP). Such soil suffers with temporary water logging conditions during the rainy season due to water impermeability (vertical and lateral both).

Plantation Establishment

A total of 24 accessions were planted in a randomized block design (RBD) with four replications in 45-cm^3 refilled pits with the same soil at a spacing of 2.5 m × 2.5 m (within a row as well as between rows), corresponding to a density of about 1600 plants ha^{-1} in September 2005. The field was irrigated after the plantation and subsequently in the summer season as and when required, preferably at 15-day intervals. A fifth replication was also planted separately for harvesting plants for biomass assessment and planting of cuttings for standardizing the vegetative propagation methods. The growth and yield were assessed annually for five consecutive years (2006–2010). Plant mortalities were replaced only in the first year of establishment. The growth observations, i.e., plant height, collar diameter, number of branches, and canopy spread (east-west and north-south), were observed in each year. Flowering, fruiting, and seeding traits were monitored third year onwards. Male/female flowers, fruit sets, seeds, and kernels were counted and the seed yield was estimated. Since the ripening of the fruits was highly asynchronous; therefore, fruits were harvested every week from December to February in each flowering year.

Physiological Measurements

The oil content of the different accessions was examined with nuclear magnetic resonance (NMR) spectrophotometer by estimating the hydrogen content of the oil (Conway and Earle 1963). Gas exchange measurements were carried out on two-year-old plants in the experimental field. Net CO_2 assimilation (A), transpiration (E), and stomatal conductance (g_s) were determined using the portable gas-exchange measuring system GFS-3000 (Walz, Effeltrich, Germany) under controlled conditions of photosynthetic photon flux density (PPFD) (1200 mmol m^{-2} s^{-1}), temperature (32°C), and leaf-to air-vapour pressure deficit (VPD) (15–20 kPa). A total of 10 leaves were measured from five different plants (one from each replication) of each accession. Instantaneous water use efficiency was calculated as the ratio of A/E. Three plants of each assorted accession were harvested for biomass assessment of each plant component. The sample (100 g) of each plant part was kept in oven at 80°C till complete dehydration. Wood density of the stem was derived from the mass/volume relationship at the DBH (diameter at breast height) point (130 cm), as described by Achten et al. (2010a, 2010b).

Propagation

Cuttings of about 20 cm length with three diameter size (1, 2, and 3 cm) of each accession were examined for determining the efficient vegetative propagation protocol. These were planted in polybags with a potting mixture of sodic soils, sand, and farmyard manure (FYM) in 1:1:1 proportion. The experiment was carried out in 2009 in a polyhouse as well as in the open-field condition to assess the root development.

Soil Sampling and Analysis

Soil samples were collected from 24 pits representing each accession at four depths (0–15, 15–30, 30–45, and 45–60) from each replication and composed of four replications, as the growth and yield are generally expressed on a mean basis. Soil sampling was carried out in 2005 before the plantations and after five years of age in 2010. Soil pH and electrical conductivity were determined with a digital pH meter. Organic carbon, available nitrogen, and phosphorus were analyzed through the methods described by Kalra and Maynard (1991). The fraction of total $CaCO_3$ (%) was estimated following the method developed by Kalra and Maynard (1991). Microbial biomass carbon was estimated by fumigation and extraction method of Vance, Brookes, and Jenkinson (1987). The dehydrogenase activity was measured following Tabatabai (1994), in which 10 g of fresh moist soil was incubated with 10 ml Tris-TTC (triphenyl tetrazolium chloride) solution for 24 hr at 30.0°C to form a reduction product of red color (triphenylformazan, TPF), and the optical density was measured at 485 nm.

Statistical Analysis

Data for various growth parameters and yield related traits were subjected to statistical analysis and presented as mean and standard deviations (SD). Analysis of variance (*F*-test) was applied to examine the significance of differences among the accessions. Critical difference among the accessions was determined for each parameter by using SPSS software package SYSTAT-9.0 version.

RESULTS AND DISCUSSION

Rooting Potential, Survival, and Growth Assessment

The rooting potential of the accessions grown in the polyhouse condition was significantly high (60–90%) from that in the field condition (30–65%) (Figure 2A; Table 1). It was also observed that older cuttings of 2- to 3-cm diameter generated a more vigorous root architecture in comparison with juvenile cuttings of about 1-cm diameter (Figure 2B). The length and basal area of stem cuttings impound the growth and development of roots in *Jatropha* plants. Short cuttings favor early sprouting, but long and thick cuttings promote more shoot and root growth (Severino et al. 2011). Plant establishment ranged from 25% to 100% in different accessions. A few accessions such as FRI E4 (25%), NBPGR Hissar Local, and CSMCRI C5 (37.5%) showed poor plant survival even after once replacement in the first year, indicating their inability to tolerate high sodicity and harsh soil conditions. Some other accessions (FRI Dehradun FRI-UA-G-0312-5 E-5, PAPL, Bangalore

Figure 2 Vegetative propagation of *Jatropha curcas* L. under poly-house condition (A) and root development with diameter size of cuttings (B) (color figure available online).

Table 1 Rooting Result in Cuttings and Field Performance of 24 Accessions of *Jatropha curcas* L. at Five Years Raised on Degraded Sodic Land in Lucknow, India

Numbers	Accession no.	Rooting (%) PHC*	Rooting (%) FC	Survival%	Plant height (cm)	Collar diameter (cm)	Number of branches (pt^{-1})	Canopy spread (cm)	DI (%)
1	NBRI - UP- LKO- J-05	66	65	100	314.6 ± 118.8	10.5 ± 3.14	43.6 ± 13.7	230.1 ± 128.0	0
2	NBRI - UP- LKO- J-18	82	30	75	243.6 ± 69.8	7.60 ± 1.49	33.1 ± 7.93	173.6 ± 78.4	12.5
3	CSMCRI-GUJ-Banas-1205-C1	70	30	100	270.3 ± 59.5	8.94 ± 2.53	41.6 ± 7.10	234.7 ± 57.8	43.75
4	CSMCRI-GUJ-Banas-1205-C2	76	55	100	304.0 ± 68.7	8.77 ± 1.72	44.0 ± 9.44	227.2 ± 54.9	56.25
5	CSMCRI-GUJ-Panch-0106-C3	70	45	100	258.1 ± 68.5	8.01 ± 1.68	39.5 ± 5.83	194.5 ± 50.2	50
6	CSMCRI-OR-Ganj-1205-C4	88	60	81.25	259.2 ± 32.4	8.45 ± 0.82	40.1 ± 5.98	208.5 ± 43.8	93.75
7	CSMCRI-OR-Ganj-1205-C5	74	65	37.5	301.2 ± 0.35	8.72 ± 0.12	43.6 ± 5.83	236.1 ± 6.19	37.5
8	NBPGR-GUJ-SKN-0605-SKNJ-2	78	55	100	323.8 ± 67.4	9.00 ± 1.33	45.6 ± 19.0	230.8 ± 61.8	25
9	NBPGR-GUJ-SKN-0605-SKN-Big	86	40	100	269.6 ± 75.6	8.20 ± 1.85	37.9 ± 6.97	197.4 ± 51.3	0
10	NBPGR-GUJ-SKN-0605-Urlikanchan	60	35	100	342.5 ± 42.9	9.77 ± 1.03	51.1 ± 6.48	289.5 ± 39.6	0
11	NBPGR-GUJ-SKN-0605-Chhatrapati	80	50	100	344.6 ± 32.0	10.0 ± 1.21	57.5 ± 12.2	280.9 ± 42.9	31.25
12	NBPGR-GUJ-SKN-0605-Hansraj	96	60	100	264.6 ± 114.0	8.45 ± 2.44	45.3 ± 14.3	209.5 ± 97.4	50
13	NBPGR Hissar Local	99	55	37.5	151.7 ± 49.7	5.35 ± 0.94	27.9 ± 2.40	107.6 ± 42.3	18.75
14	CRIDA Hyderabad JJ-05	86	45	93.75	264.8 ± 22.5	8.04 ± 0.58	44.9 ± 4.01	224.4 ± 40.5	37.5
15	CRIDA Hyderabad LJ-05	86	50	100	253.8 ± 94.0	7.92 ± 2.41	39.5 ± 11.4	197.6 ± 102.8	12.5
16	FRI Dehradun FRI-UA-G-0312-5 E-1	94	55	87.5	235.5 ± 75.2	7.17 ± 1.34	33.2 ± 6.23	166.3 ± 49.2	12.5
17	FRI Dehradun FRI-UA-G-0312-5 E-2	91	35	100	195.6 ± 80.8	6.32 ± 1.73	32.3 ± 7.80	132.6 ± 69.0	60
18	FRI Dehradun FRI-UA-G-0312-5 E-3	95	45	87.5	201.1 ± 87.2	6.71 ± 1.64	31.8 ± 6.87	149.9 ± 79.0	37.5
19	FRI Dehradun FRI-UA-G-0312-5 E-4	96	45	25	149.6 ± 22.1	5.68 ± 0.97	27.6 ± 5.18	102.1 ± 31.3	50
20	FRI Dehradun FRI-UA-G-0312-5 E-5	80	50	75	114.0 ± 28.4	4.77 ± 0.62	25.6 ± 1.91	81.2 ± 20.9	54.55
21	PAPL, Bangalore JPH 009	82	60	75	240.3 ± 44.9	8.08 ± 0.95	38.9 ± 8.19	197.0 ± 44.8	0
22	PAPL, Bangalore JPH108	70	55	75	240.4 ± 73.3	7.70 ± 1.37	36.5 ± 4.66	163.3 ± 65.2	35.71
23	EXCEL, Mumbai BHAVO 405 C1	60	55	81.25	279.4 ± 54.8	8.57 ± 1.79	41.6 ± 9.98	191.7 ± 54.0	43.75
24	CRIDA-JR-06	80	50	68.75	123.9 ± 32.2	5.73 ± 0.29	32.2 ± 2.46	88.4 ± 9.14	0
	CD	–	–	–	101.28	2.81	14.56	87.55	

*Rooting percentage was calculated out of 50 cuttings planted. PHC = Poly-house condition, FC = field condition, DI = disease infestation.

JPH 009 and PAPL, and Bangalore JPH108) though survived well (75%), but suffered poor growth (Table 1). Besides, another group (NBRI-UP-LKO-J-05 and CSMCRI, OR-KMP-C4) grew well vegetatively but could not produce a reasonable seed yield. Plant height (114.06–344.62 cm) varied significantly ($P < 0.05$) among different accessions. The low height of some accessions such as FRI-UA-G-0312-5 E-5 and CRIDA-JR-06 may be attributed to their poor adaptability to sodic soils. Collar diameter varied from 4.77 to 10.15 cm in various accessions. These differences were statistically significant ($P < 0.01$) among various accessions. NBPGR Chhatrapati, followed by NBRI J05, was better in collar diameter over the others. There were marked differences in the number of branches (25–57 branches per plant) among different accessions. Branching was profuse in some accessions such as NBPGR Chhatrapati (57) and Urlikanchan (51), while it was poor in FRI-UA-G-0312-5 E-5 (25) and E-4 (27) due to their lesser growth. Accordingly, canopy spread varied greatly from 81.25 to 289.56 cm in different accessions, with the minimum in FRI-UA-G-0312-5 E-5 and the maximum in NBPGR Urlikanchan, depending on the branching pattern. It has been observed that unlike the presumptions, JCL suffers a lot from several diseases. Viral infections are quite common among them. The frequency of virus-infected plants varied greatly from 12% to 94% in different accessions (Table 1). Accessions such as CSMCRI-C4 were most susceptible to virus attack (94%), followed by FRI Dehradun-E2 (60%). In some accessions, viz. NBRI-J-05, NBPGR-SKN-Big, NBPGR-Urlikanchan, and PAPL JPH-0090, none of the plants was found to be infected with virus, indicating their resistance to viral disease. Jatropha Mosaic Virus (JMV) spreads fast through sap transmission (Tewari et al. 2007) and causes a severe disease incidence, sometimes in the major populations of JCL, as noticed in one of our trials at NBRI, Lucknow (Sidhu et al. 2010).

Flowering, Fruiting, and Seed Yield

Flowering and fruiting was asynchronous in all the accessions. Consequently, the emergence of flowers and the setting of fruits on the same plant are seen almost round the year in different stages of development. However, two flowering peaks were visually observed in May and October. Flowering ranged from 28% to 100%, and likewise, fruiting was observed to range from 23% to 98% in different accessions. The lowest flowering and fruiting was recorded in CRIDA JR-06, similar to its growth pattern. The female:male ratio ranged from 1–18 to 1–30 (Table 2). It was similar to earlier findings (Raju and Ezradanam 2002). The seed:fruit and kernel:seed ratio did not vary much among the accessions. The seed:fruit ratio ranged from 0.55 to 0.74 g and the kernel:seed ratio from 0.37 to 0.77 g. The highest seed:fruit ratio was noted in NBPGR-Urlikanchan. The 100 seed test weight ranged from 46.5 g (PAPL, Bangalore JPH 009) to 78 g (NBRI J-05) across the different accessions. The seed yield (34.41–246 g pt^{-1}) in different accessions showed large variations among them. The total seed yield recorded at the fifth-year growth stage was greatest in NBPGR-Urlikanchan and lowest in CRIDA-JR-06 accession (Table 2), although it is still too less to be exploited economically on a commercial scale. Data from various reports, conference proceedings, expected assessments, and assumptions indicate that the seed yield of JCL varies from 0.2 kg to more than 2 kg $plant^{-1}$ or 2–5 tonne (t) ha^{-1} and even 7.8–12 t ha^{-1} (Jones and Miller 1992; Tewari 2007; Jongschaap et al. 2007; Achten et al. 2008). However, the present yield is far below from such expectations, which could be improved by selections and systematic breeding programs between diverse lines for developing a suitable high-yielding variety for sodic soil sites. A breeding program based on

Table 2 Flowering-Fruiting and Yield-Related Traits and Oil Content of 24 Accessions of Five-Year-Old *Jatropha curcas* L. Plantation Growing on Sodic Land

Numbers	Name of accessions	Flowering%	Fruiting%	F:M ratio	S:F ratio	K:S ratio	SW	SY (g pt^{-1})	OC (%)
1	NBRI - UP- LKO- J-05	79.1 ± 3.60	86.54 ± 9.99	01 : 20	0.55 ± 0.10	0.71 ± 0.18	78	85.4 ± 40.8	11.34
2	NBRI - UP- LKO- J-18	75.6 ± 7.31	68.02 ± 12.2	01 : 22	0.60 ± 0.04	0.65 ± 0.08	67.3	169.0 ± 82.5	28.05
3	CSMCRI-GUJ-Banas-1205-C1	100 ± 0.00	87.5 ± 12.5	01 : 23	0.66 ± 0.03	0.63 ± 0.05	74	177.6 ± 48.0	26.59
4	CSMCRI-GUJ-Banas-1205-C2	97.9 ± 3.60	81.3 ± 12.5	01 : 19	0.68 ± 0.04	0.69 ± 0.07	65	134.5 ± 51.8	23.14
5	CSMCRI-GUJ-Panch-0106-C3	87.5 ± 0.00	86.3 ± 1.03	01 : 23	0.70 ± 0.12	0.60 ± 0.12	63	128.7 ± 44.8	27.16
6	CSMCRI-OR-Ganj-1205-C4	91.2 ± 9.42	90.9 ± 9.39	01 : 23	0.68 ± 0.01	0.63 ± 0.26	60	87.9 ± 66.2	20.33
7	CSMCRI-OR-Ganj-1205-C5	73.6 ± 32.3	73.6 ± 32.4	01 : 23	0.63 ± 0.0	0.77 ± 0.03	77	130.6 ± 68.2	25.31
8	NBPGR-GUJ-SKN-0605-SKNJ-2	93.8 ± 0.00	89.0 ± 4.08	01 : 21	0.61 ± 0.05	0.68 ± 0.27	76	100.3 ± 38.0	33.28
9	NBPGR-GUJ-SKN-0605-SKN-Big	81.3 ± 10.8	82.4 ± 12.5	01 : 20	0.62 ± 0.02	0.68 ± 0.07	60	164.3 ± 66.6	28.96
10	NBPGR-GUJ-SKN-0605-Urlikanchan	100 ± 0.00	97.9 ± 3.60	01 : 20	0.74 ± 0.10	0.60 ± 0.06	65.5	246.0 ± 40.6	26.95
11	NBPGR-GUJ-SKN-0605-Chhatrapati	100 ± 0.00	93.7 ± 6.25	01 : 22	0.68 ± 0.07	0.54 ± 0.04	70	191.3 ± 62.6	29.85
12	NBPGR-GUJ-SKN-0605-Hansraj	77.0 ± 7.21	87.0 ± 16.2	01 : 23	0.72 ± 0.07	0.55 ± 0.11	64	182.7 ± 46.9	33.85
13	NBPGR Hissar Local	59.7 ± 40.9	44.2 ± 27.4	01 : 29	0.73 ± 0.11	0.63 ± 0.04	60	104.4 ± 63.0	29.95
14	CRIDA Hyderabad JJ-05	95.7 ± 3.74	93.4 ± 6.67	01 : 24	0.68 ± 0.02	0.37 ± 0.10	58.5	44.5 ± 27.1	24.21
15	CRIDA Hyderabad LJ-05	70.8 ± 7.22	76.3 ± 12.0	01 : 18	0.69 ± 0.09	0.56 ± 0.11	56	123.5 ± 48.7	30.28
16	FRI Dehradun FRI-UA-G-0312-5 E-1	80.0 ± 9.79	84.0 ± 13.2	01 : 20	0.68 ± 0.01	0.64 ± 0.03	55	110.5 ± 54.7	24.31
17	FRI Dehradun FRI-UA-G-0312-5 E-2	75.0 ± 27.2	46.8 ± 12.2	01 : 22	0.68 ± 0.07	0.59 ± 0.09	65	72.7 ± 58.1	30.10
18	FRI Dehradun FRI-UA-G-0312-5 E-3	75.9 ± 17.0	66.0 ± 9.39	01 : 25	0.63 ± 0.06	0.58 ± 0.03	56	106.7 ± 91.0	24.13
19	FRI Dehradun FRI-UA-G-0312-5 E-4	60.4 ± 48.5	60.4 ± 48.5	01 : 30	0.58 ± 0.11	0.61 ± 0.11	60	64.1 ± 37.8	28.87
20	FRI Dehradun FRI-UA-G-0312-5 E-5	54.2 ± 15.0	39.8 ± 16.2	01 : 18	0.68 ± 0.15	0.55 ± 0.12	67	37.2 ± 14.2	24.11
21	PAPL, Bangalore JPH 009	83.3 ± 8.33	65.9 ± 13.8	01 : 23	0.66 ± 0.04	0.62 ± 0.10	46.5	116.2 ± 65.7	32.02
22	PAPL, Bangalore JPH108	91.6 ± 14.4	80.5 ± 9.62	01 : 24	0.72 ± 0.13	0.66 ± 0.14	62	89.3 ± 73.7	11.03
23	EXCEL, Mumbai BHAVO 405 C1	77.2 ± 12.8	75.2 ± 11.4	01 : 21	0.65 ± 0.07	0.60 ± 0.14	75	127.5 ± 44.8	30.05
24	CRIDA-JR-06	27.8 ± 0.00	22.7 ± 6.43	01 : 20	0.63 ± 0.00	0.63 ± 0.00	65	34.4 ± 00.0	25.59

F:M, S:F, and K:S are female:male, seed:fruit, and kernel:seed ratio, respectively. SW = 100 seed test weight (g), SY = seed yield at fifth-year growth, OC = oil content.

genetic diversity determined through an AFLP (amplified fragment length polymorphism) analysis is underway at our own institute, CRIDA, Hyderabad, and Anand Agricultural University, Gujarat, with the support of CSIR.

The reasons of such a low yield were explored, among them, besides the soil constraints, virus infestation, pollinator's scarcity, frequent drop of female flowers, and fruit-sap suckers/capsule borer were found to play a significant role in yield limitations. The number of male flowers was many times greater than that of female flowers, but infrequent visits of potential pollinators (medium- to large-size wasp, bees, and flies) cause poor fertilization, leading to low fruit (embryo) development and seed set. Furthermore, the flowers are light greenish-yellow to white and rather small in size, and are usually invisible due to the greenish background or superimposed leaves and less attractive to the pollinators (Raju and Ezradanam 2002). It is suggested that the reduced yield of JCL might be a result of reduced reproductive success. It is observed that honeybees are the prime pollinators, which may vary according to size, age, planting density, and climatic condition of JCL plantations. The fruit of JCL has a good moisture-retaining capacity due to the fibrous nature of the hull, which invites fungal infection. If the moisture is retained for a prolonged time, it causes vivipary, which results in poor seed yield (Deore and Johnson 2008).

Superior Selections

Accessions such as CSMCRI-C-1, NBPGR Chhatrapati, Urlikanchan, and Hansraj were found to be relatively good on the basis of seed yield per plant. Their growth rate, adaptability to stress soil conditions, branches, and canopy spread may not be essentially higher as compared with those of other accessions, which indicates that growth and yield are not well correlated in JCL. NBPGR-Urlikanchan and Chhatrapati showed their consistently higher growth characteristics (height, diameter, branches, and canopy) over the five years in comparison with CSMCRI-C-1 and NBPGR-Hansraj (Figure 3). Conversely, in an early screening at two years of age, CSMCRI-C-1 had the highest photosynthetic rate (A), stomatal conductance (g_s), transpiration rate (E), and water use efficiency (A/E) among the four accessions (Table 3). It appears that plant physiological responses to a particular stress in field conditions are difficult to measure precisely as several environmental factors (climatic, edaphic, and biotic) interact with the plants in different ways, which cannot be controlled completely (Maes et al. 2009). The g_s and A/E of these four accessions were relatively high compared with those of other *J. curcas* in pots (Rajaona, Asch, and Brueck 2010). Li Guo (2002) has reported the low water use efficiency of *J. pandurifolia* (3.68) and *J. gossypifolia* (2.52) in mmol CO_2 mol H_2O^{-1} in comparison with our observations on *J. curcas*, which supports its drought- and salt-resistant nature to grow well even in low rainfall zones. The early growth of JCL (two-year-old) on the sodic land was significantly low compared with that in some other studies at comparable age (Behera et al. 2010; Srivastava et al. 2011), which might be due to sodicity stress and other inhospitable conditions prevailing at our site. However, these accessions shortlisted for sodic soil sites have not been always superior at other degraded sites (unpublished data). It indicates the dominant role of environmental (abiotic) factors over the narrow genetic base on the growth behavior (Kaushik et al. 2007). The wood density of these four accessions varied significantly from 0.18 (NBPGR-Chhatrapati) to 0.32 (NBPGR-Hansraj) g cm^{-3} (Figure 4A), comparable with earlier findings (Achten et al. 2010a, 2010b). The highest biomass production by NBPGR-Hansraj could not sustain its seed yield as good as that in other three assorted accessions (Figure 4B and C), but it maintained its maximum record of oil content

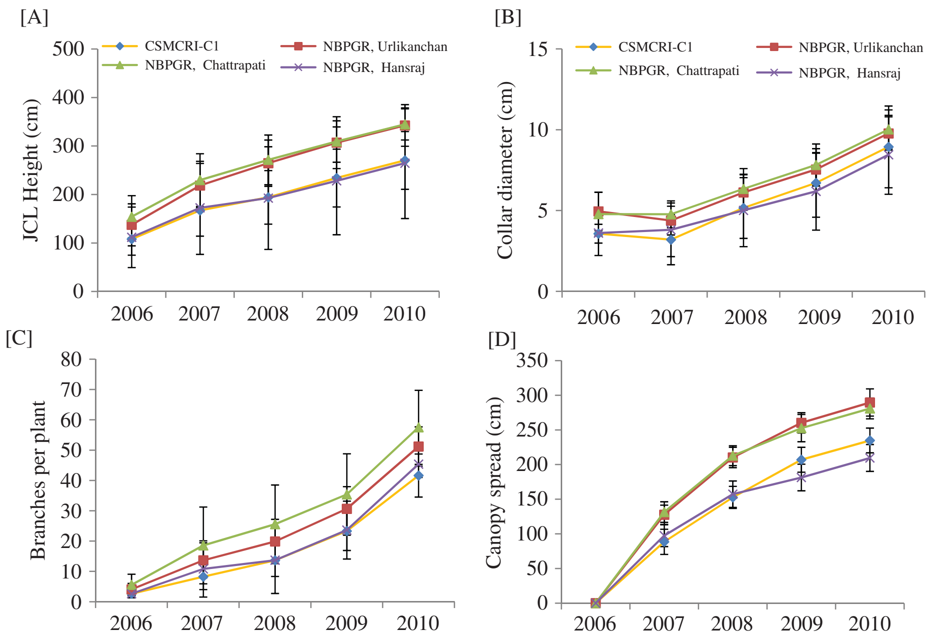

Figure 3 Growth performance of best four accessions of *Jatropha curcas* L. during five years. A = height, B = collar diameter, C = number of branches, D = canopy spread (color figure available online).

Table 3 Comparison of Gas Exchange Parameters Among Four Assorted Accessions of *Jatropha curcas* L Under Field Condition on Two-Year-Old Plants

Name of accessions	Photosynthetic rate (μmol m^{-2} s^{-1})	Stomatal conductance (mmol m^{-2} s^{-1})	Transpiration rate (mmol m^{-2} s^{-1})	Water use efficiency (mmol CO_2 mol H_2O^{-1})
CSMCRI-GUJ-Banas-1205-C1	11.04 ± 0.62	214.56 ± 24.35	2.32 ± 0.19	6.90 ± 1.13
NBPGR-GUJ-SKN-0605-Urlikanchan	5.73 ± 1.19	53.35 ± 8.44	1.25 ± 0.23	4.60 ± 0.36
NBPGR-GUJ-SKN-0605-Chhatrapati	8.79 ± 1.82	120.99 ± 16.45	1.87 ± 0.41	5.09 ± 0.34
NBPGR-GUJ-SKN-0605-Hansraj	9.26 ± 1.12	87.37 ± 11.42	1.71 ± 0.22	5.34 ± 0.39

Values are mean of five plants of each accession ± SD. $P < 0.05$ between plants.

throughout the years (Figure 4D). An attempt was made to examine the correlation of seed yield (y) with plant height (x_1) and branches (x_2), which indicated weak correlations of yield with growth characteristics (Figure 5). This is one of the reasons of the low yield of JCL, which suggests the need of developing a genotypically superior variety where the growth and yield may be strongly correlated. As such, the photosynthetic assimilate needs to be transported to the reproductive parts.

Comprehensive research and experimentation is still required to justify the claims of successful plantations on different types of sodic lands, as merely the establishment of plants does not render satisfactory yield. *Jatropha* exhibits great variability in productivity between individual plants; therefore, long-term productivity trials need to be carried out (at least for 10 years). The annual seed production per plant can range from about 200 g

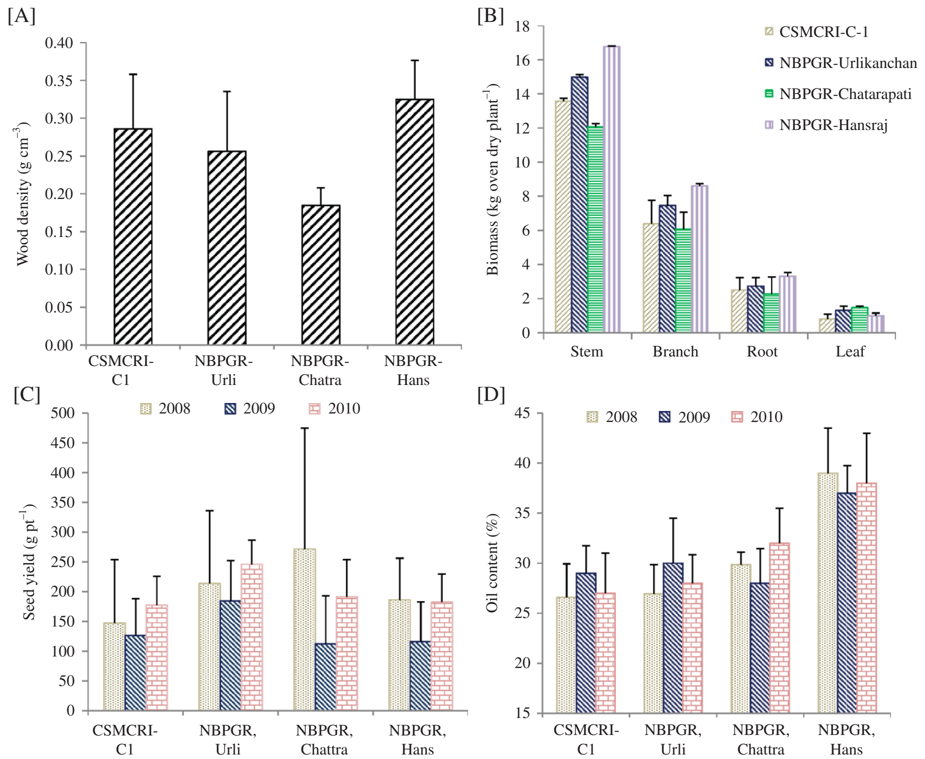

Figure 4 Wood density (A), biomass (B), seed yield (g pt^{-1}), and oil content (%) of four assorted accessions of *Jatropha curcas* L (color figure available online).

to more than 2 kg in different edapho-climatic conditions after five years; however, at later stages, a decline in the productivity has been reported as plantations age. On our site, JCL bore viable seeds only once in a year during the winter season (December to January); however, Carels (2009) has reported the total seed production with three harvests per year, ranging from 2000 to 4000 kg ha^{-1} and typically around 3200 kg ha^{-1}, corresponding to about 1.5 t oil ha^{-1} with an annual rainfall of 700–800 mm. These estimates appear to be difficult to achieve in India unless a superior variety is evolved.

Soil Properties

Significant reduction in soil pH and electrical conductivity (EC) showed a positive impact of JCL plantation on soil reclamation (Table 4). The nitrogen and phosphorus contents in the soil have improved considerably due to the addition of organic matter through litter fall, root mortality, and weed turnovers. In addition, soil microbial biomass carbon and the dehydrogenase activity, which are considered as soil improvement indicators, have increased manifold after five years of plantation. Plantations of JCL on degraded lands are supposed to offset the degraded soil properties to varying extents corresponding to their growth and age (Kaushik et al. 2007; Abhilash et al. 2010; Garg et al. 2011). *J. curcas* has also been shown to improve the structural stability, and carbon and nitrogen contents of degraded entisol of India (Ogunwole et al. 2007, 2008).

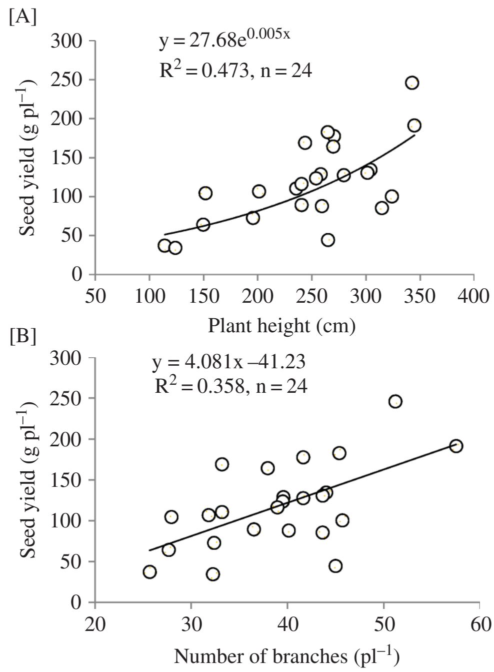

Figure 5 Correlation of seed yield (g) with plant height (A) and branches (B) among 24 accessions of *Jatropha curcas* L.

CONCLUSIONS

The study concludes that the site-specific selections of JCL based on superior growth, yield, and oil traits be identified for a systematic breeding program to develop a high-yielding variety for sodic soil sites commonly found in north India to integrate the different positive characters of NBPGR-Chhatrapati (yield), Hansraj (oil), and CSMCRI-C1(WUE). The present status of seed yield at five years of age cannot be economically exploited on a commercial scale. We have screened out four best accessions among the 24 on the basis of seed yield. Although seed yield has not become stabilized yet in five years as the evaluation of the perennial plant (shrub/tree) for optimum fruiting and seed production may take many more years to get stable yield estimates, which will be confirmed in subsequent years if an accession maintains its lead consistently onwards. However, before undertaking the extension of JCL on large-scale farmers' community lands, this plant still needs considerable research through conventional as well as molecular breeding to domesticate a variety first that could be suitable for cultivation on degraded lands with minimum inputs and can produce a reasonable yield of at least 4–5 t ha^{-1} with oil content of around 35–40% for making the JCL-biodiesel an economically feasible venture. At least, it must generate a 1200 kg ha^{-1} oil yield to become quite competitive with the 375 kg ha^{-1} yield for soybean in the United States and the 1000 kg ha^{-1} yield for rapeseed in Europe.

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Table 4 Changes in Soil Properties up to 60-cm Depth After Five Years of Plantation of *Jatropha curcas* L. on Degraded Sodic Land (Mean ± SD)

Soil properties	Depth (cm)	2005	2010	Improvement (%)
Soil pH	0–15	8.58 ± 0.28^a	7.95 ± 0.02^b	8
	15–30	9.15 ± 0.34^a	8.98 ± 0.11^b	2
	30–45	9.41 ± 0.36^a	9.34 ± 0.13^a	0.75
	45–60	9.55 ± 0.37^a	9.55 ± 0.62^a	0
Electrical conductivity (μS cm^{-1})	0–15	372.0 ± 93.9^a	293.0 ± 11.5^b	22
	15–30	409.2 ± 33.8^a	376.0 ± 11.5^b	9
	30–45	459.6 ± 35.8^a	423.3 ± 22.8^a	8
	45–60	574.3 ± 44.5^a	566.0 ± 38.3^a	2
Organic carbon (%)	0–15	0.45 ± 0.10^a	1.42 ± 0.16^b	69
	15–30	0.16 ± 010^a	1.04 ± 0.24^b	85
	30–45	0.10 ± 0.06^a	0.21 ± 0.16^b	53
	45–60	0.08 ± 0.04^a	0.10 ± 0.03^a	20
Available nitrogen (μg g^{-1})	0–15	37.3 ± 0.60^a	51.8 ± 6.50^b	28
	15–30	17.5 ± 0.79^a	25.5 ± 2.80^b	32
	30–45	13.2 ± 0.57^a	19.8 ± 5.49^b	34
	45–60	8.20 ± 1.88^a	9.87 ± 4.50^b	17
Available phosphorus (μg g^{-1})	0–15	32.6 ± 4.34^a	39.6 ± 3.15^b	18
	15–30	23.5 ± 2.95^a	26.2 ± 1.07^b	11
	30–45	21.8 ± 0.64^a	23.9 ± 3.30^b	19
	45–60	19.2 ± 2.96^a	19.5 ± 3.53^a	2
$CaCO_3$ (%)	0–15	4.31 ± 0.40^a	3.19 ± 0.50^b	26
	15–30	3.06 ± 0.82^a	2.48 ± 0.47^b	19
	30–45	1.94 ± 0.68^a	1.94 ± 0.29^a	0
	45–60	1.72 ± 0.63^a	1.72 ± 0.39^a	0
Microbial biomass carbon (μg g^{-1})	0–15	90.0 ± 13.2^a	413.3 ± 36.9^b	79
	15–30	93.3 ± 7.64^a	213.3 ± 27.5^b	57
	30–45	76.7 ± 10.4^a	106.3 ± 15.5^b	28
	45–60	58.3 ± 5.78^a	71.5 ± 15.3^b	19
Dehydrogenase (μTPF g^{-1} hr^{-1})	0–15	5.59 ± 0.94^a	61.0 ± 5.07^b	91
	15–30	3.56 ± 0.78^a	37.9 ± 4.69^b	90
	30–45	2.80 ± 0.38^a	15.0 ± 2.29^b	82
	45–60	2.37 ± 0.58^a	10.4 ± 2.41^b	78

Different lowercase letters between 2005 and 2010 shows significant differences at $P < 0.05$.

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