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Agro-technology of *Jatropha curcas* for diverse environmental conditions in India

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A B S T R A C T

Jatropha curcas has been widely planted without knowing its standard package of practice for optimizing the yield. Therefore, a standardized agro-technology of *Jatropha* is required. With this purpose, in this study an elite accession of *Jatropha* was planted at seven sites in India, covering a range of edapho-climatic conditions. Three experimental trials (spacing, pruning and irrigation and fertilizer) were carried out wherein its growth and yield performance were assessed for five years (2007–2012) at all the sites. The growth characters like plant height and number of branches showed significant variations among the sites and the effects of treatments were not uniform across the sites, indicating that site-specific package of practices should be followed instead of adopting the general recommendations. The seed yield was disappointing to recommend it randomly for large scale plantations on degraded lands in India. But results from the multi-location trials have shown good prospects at semi-arid (Bhavnagar) and drylands (Hyderabad); where plants in close spacing (2×2 m) produced significantly higher seed yield per unit area upto 1.4 t ha^{-1} (Bhavnagar) in comparison to wide spacing. Pruning showed a negative effect on seed yield during initial five years. We found that the following prescription was sufficient to optimize the yield on India's degraded soils: irrigation at a 30 day interval, and for each planting hole 2 kg of Farm Yard Manure (organic manure) and nitrogen, phosphorous and potassium at 10 g, 20 g, and 10 g, respectively.

1. Introduction

National mission on biodiesel in India has promoted the plantation of *Jatropha curcas* (*Jatropha*) at massive scale and many international agencies have also shown to come forward all over the tropical world [1,2]. However, several aspirations did not rely on sound scientific base [3–5], and the hyped claims hold the risk of unsustainable practices [6]. Partial information is available about the silviculture/agro-technology and management of *Jatropha* plantations in the long rotation cycle. The main knowledge gaps are noticed in the cultivation part particularly its stress tolerant nature [6,7], growth and yield in response to inputs [3–5,8]. This information is not important as long as *Jatropha* is considered a wild

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and undomesticated plant showing great variability in productivity between individual plants [8]. But when it is considered as a potential biodiesel crop, we must work-out its standardized agro-technology for each bio-geographic region. No doubt, it may be cultivated in a wide range of environmental conditions (habitat), but the low seed yield under stress conditions limits its scope in regions with arid and semi-arid climates [9,10]. Thus the propagation of the elite planting material, their growth and yield performance, soil management, standardized agro-technology, mechanized seed harvest and dehulling process need to be fully understood. As a promising feedstock of second generation biofuel, *Jatropha* is planted on marginal land in South Africa [10], China [11], Zimbabwe [12] and India [13,14] but its economic viability as a biofuel source at the current techno-commercial values have been found infeasible [15,16].

Despite the several merits, *Jatropha* could not be domesticated yet as a potential oil crop and it is still considered as a semi-wild plant. Large scale plantations may give it a semi-wild status, which will determine its domestication prospects in due course of time depending on its benefit: cost ratio. It has been advocated that *Jatropha* is drought tolerant and produce significant seed yield of acceptable quality with minimum water requirements compared to other crops [17]. It grows well on degraded soils of low fertility. In fact, this assumption is based on the premise that such soils have low potential for economically viable agriculture and their use for the cultivation of *Jatropha* would not be in conflict with food production. Since arable land cannot be diverted for *Jatropha* cultivation, its prospects on poor, marginal, degraded, derelict, denuded, desolated and abandoned lands are being looked for biofuel production in the country. Council of Scientific and Industrial Research (CSIR) has systematically evaluated its potential in terms of productivity and oil yield in a wide range of agro-climatic conditions in India under New Millennium Indian Technology Leadership Initiative (NMITLI) project (2005–2012). The main objective of this project was to evaluate sustainability of various land types and edapho-climatic conditions for the economic cultivation of *Jatropha* in diverse habitat.

Reliable scientific data on its agronomy are currently lacking despite its considerable scope to optimize production in a wide range of agro-ecological conditions. Consequently, attempt was made to assess the effects of different agronomic treatments (spacing, pruning, irrigation and fertilization) on growth and seed yield of *Jatropha* at seven locations of India. Furthermore, we have tried to address other related issues (soil properties, effect of climate and diseases incidence) which contribute in standardization of agro-technology of *Jatropha* for optimizing the climate based yield. This will assist in to domesticate and cultivate *Jatropha* on degraded (non-arable) lands in India.

2. Materials and methods

2.1. Study sites

Study was carried out at seven locations such as sub-tropical Lucknow (80°45′E 26°40′N) in Uttar Pradesh, arid Jodhpur (26.28°N 73.02°E) in Rajasthan, semi arid Bhavnagar (21.76°N 72.15°E) in Gujarat, dry tropical Hyderabad (17.366°N 78.476°E) in Andhra Pradesh, wet tropical Dehradun (30.3157 N 78.0336 E) in Uttrakhand, sub-tropical Jorhat (26.75 N 94.22 E) in Assam and sub-tropical Naharlagun (27°06′11″93°N 42) in Arunanchal Pradesh. The latter two sites belong to north east states of India, while others are situated in north, south and western parts of India (Fig. 1).

2.2. Climate and soil of study sites

Field experiments were carried out in different agro-climatic zones where rainfall, temperature and humidity varied considerably (Fig. 2). Naharlagun site has received the highest (3106 mm/year) average annual rainfall (2007–2012) while it was lowest (348 mm/year) at Jodhpur (Fig. 2A). The mean annual temperature for the last five years was highest (27.7 °C) at Jodhpur and lowest (21.2 °C) at Dehradun (Fig. 2B). Relative humidity (%) was highest (79%) at Jorhat and lowest (45%) at Jodhpur (Fig. 2C). These features differentiate the sites as arid (Jodhpur), semi arid (Bhavnagar and Lucknow), dry land (Hyderabad), humid (Dehradun) and wet (Jorhat and Naharlagun) climatic regions.

Soil properties of study sites where trials were carried out, are described in Table 1. The sites varied widely in term of soil order, like Alfisol, Entisol, Inceptisol, Mollisol, Aridisol and Ultisol. Textures of the experimental soils were sandy loam to clay and pH varied from alkaline to acidic nature. Lucknow site was highly sodic (the highest pH) [18–20] followed by Jodhpur (moderate pH). Bhavnagar, Hyderabad and Dehradun sites were almost neutral soils, whereas, Jorhat and Naharlagun sites were relatively acidic in nature. Electrical conductivity (EC) of the alkaline soils varied from (400–1000 $\mu S\ m^{-1}$) at Lucknow and Bhavnagar in a reverse order with respect to soil depth. EC was minimum (150 $\mu S\ m^{-1}$) at Dehradun site. Soils of Jodhpur, Hyderabad and north-east states have a modest range of 100–300 $\mu S\ m^{-1}$ EC. Dehradun and north-east states are relatively rich in soil organic carbon (OC) content (6–9 $g\ kg^{-1}$), whereas, Hyderabad and Lucknow sites were very poor in OC (2–3 $g\ kg^{-1}$) content. Jodhpur and Bhavnagar sites showed a modest range of organic carbon (3–6 $g\ kg^{-1}$).

Available N in the soil was greatest at Dehradun site (>132 $mg\ g^{-1}$) and lowest at Jodhpur (<25 $mg\ g^{-1}$). Jorhat, Naharlagun and Bhavnagar sites consisted of a modest range of available N, whereas Jodhpur, Hyderabad and Lucknow sites had a low N content (≈50 $mg\ g^{-1}$). However, in surface soil of Lucknow (0–15 cm) measured about 125 $mg\ g^{-1}$ N content, but it reduced drastically in the lower depth to below 50 $mg\ g^{-1}$. Sites of north-east states have a very high available P concentration in their soils (40–80 $mg\ g^{-1}$), whereas Lucknow, Jodhpur and Hyderabad sites have a modest range of about 20 $mg\ g^{-1}$ P. Soil of Dehradun is low in available P (5 $mg\ g^{-1}$), whereas, Bhavnagar soil is under severe deficit of available P (<2 $mg\ g^{-1}$). Most of the soils were rich in potassium (K) content (100–200 $mg\ g^{-1}$) except at Lucknow and Jodhpur sites, which almost consisted of relatively low (40–50 $mg\ g^{-1}$) K in the soils. Potassium (K) content in soils of Dehradun was in the middle range of the two extremes (70–90 $mg\ g^{-1}$).

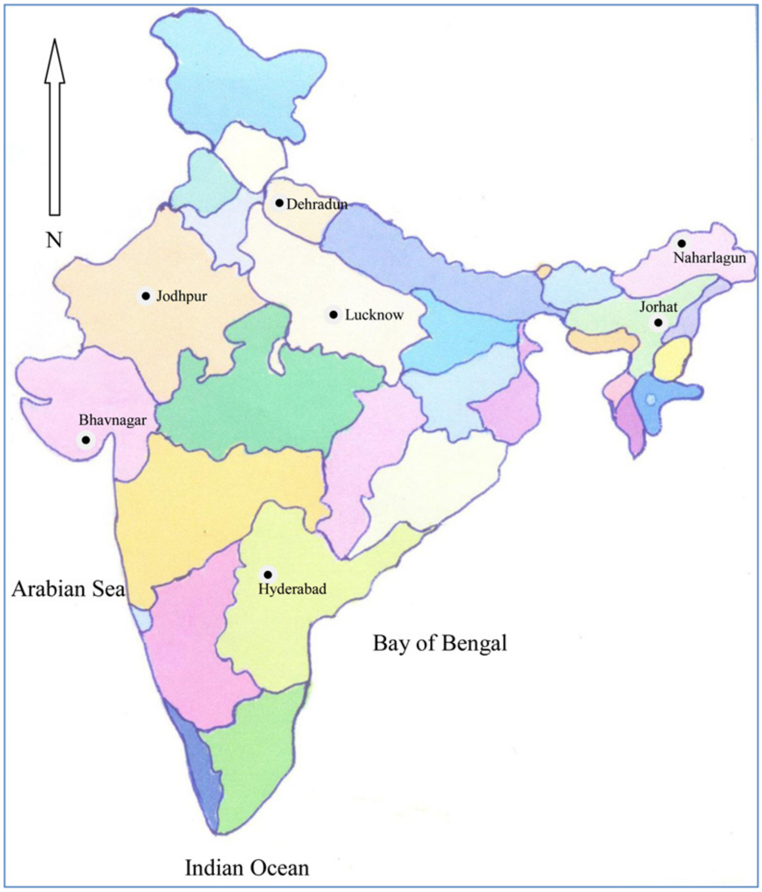

Fig. 1 – Locations of the *Jatropha curcas* study sites in India.

2.3. *Selection of an elite accession of* Jatropha *for plantation*

Several criteria and descriptors have been developed to select elite planting material for mass multiplication and extension of field plantations [21–23]. In order to assess the suitable planting material, a large number of accessions of *Jatropha* were evaluated at different sites, efforts were made to collect and test germplasm from different bio-geographic regions of India such as Uttrakhand, Gujarat, Rajasthan, Bihar, Chhattisgarh, Punjab, Himachal Pradesh, Andhra Pradesh, Madhya Pradesh, Orissa and North-East states of India. Of these, 14 accessions were assorted from the multilocation trials for further progeny test and hybridization program. An accession i.e. CSMCRI-GUJ-Banas-0106-C-3 (IC No. 559365, oil 30%) performed well at most of the sites was selected for the standardization of agro-technology across the locations.

2.4. *Plantation procedure and treatments*

Three trials were laid out to standardize the agro-technology of *Jatropha* for optimizing its seed yield which showed wide variations with environmental conditions. Four month old seedlings of the aforesaid accession were established during August to October, 2007 in refilled planting holes of 45 cm^3 mixed with the soil and compost manure in spacing and pruning trial, whereas in irrigation cum fertilizer trial, manure or chemical fertilizer was applied in different combinations.

2.4.1. *Spacing*

A spacing trial was laid out at all the study sites to standardize the plant spacing for optimizing the growth and productivity per unit area. There were four spacing treatments viz. 2×2 m, 2.5×2.5 m, 3×3 m and 4×4 m. Plants were raised in five replicates in randomized block design. Each treatment had sixteen plants per replicate ($16 \times 5 = 80$ plants per treatment).

2.4.2. *Pruning*

A pruning trial was carried-out in randomized block design (RBD) with five replicates. Treatments were applied at different locations in winter season (dormant period) when the plant grew up to 1 m height (after one year growth). Proper pruning of the branches during dormant period seems to be an efficient technique to induce further branches [13]. The aerial part of *Jatropha* was cut off at 30, 45 and 60 cm height from the ground. One treatment was set as control where pruning was not done. The pruning was commenced

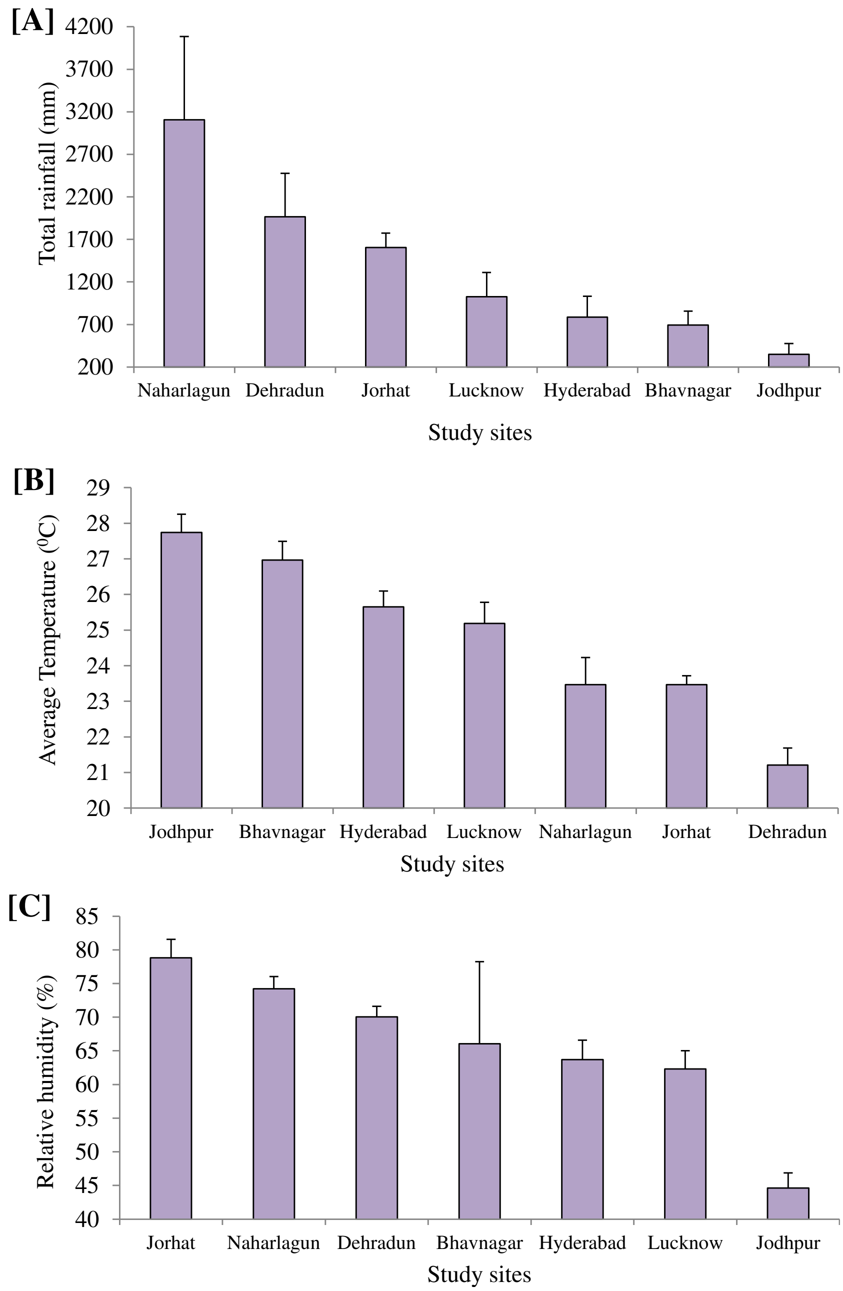

Fig. 2 – Rainfall (mm) [A], average temperature (°C) [B] and relative humidity (%) [C] of different study sites in India. Average of last six years (2006–2011).

in January–February, 2007. Plant spacing was 2.5 × 2.5 m apart.

2.4.3. *Irrigation cum fertilizer trial*

This experiment was laid out in split plot design with four replications at four levels of irrigation treatments in main plot (I_0 = Life saving irrigation 60 days or as required, I_1 = 15 days, I_2 = 30 days, and I_3 = 45 days at five locations, whereas, at Dehradun site I_1 treatment was replaced by an I_4 treatment (60 days) due to humid region). Five levels of fertilizer treatments for each planting holes (F_0 = no organic manure i.e. FYM, F_1 = 2 kg FYM, F_2 = 5 kg FYM, F_3 = Nitrogen 10 g + P 20 g, K 10 g, F_4 = 2 kg FYM + Nitrogen 10 g + P 20 g + K 10 g) were arranged in sub plot. This experiment was established at five locations only, excluding Jorhat and Naharlagun sites, where a separate RBD trial was conducted for the same fertilizer treatments. As these two sites belong to high rainfall zones; irrigation treatments were not studied. Plants were spaced at a square spacing of 2.5 × 2.5 m.

2.5. *Statistical analysis*

Data for various growth parameters and yield related traits were subjected to statistical analysis and presented as mean

Table 1 – Soil properties of different study sites undertaken for agro-technology experiments. Values are mean of three replicates.

Soil properties	Depth (cm)	Study sites							
		Lucknow (Sodic)	Jodhpur (Arid)	Bhavnagar (Semi-arid)	Hyderabad (Dry-land)	Dehradun (Humid)	Jorhat (Wet acidic)	Naharlagun (Wet acidic)	Mean
Soil pH	0–15	9.31	8.20	6.70	6.06	6.50	5.88	5.60	6.89
	15–30	9.85	8.19	6.70	6.06	6.30	5.90	5.85	6.98
	30–45	10.34	8.20	6.90	5.95	6.30	6.16	6.10	7.14
	45–60	10.61	8.21	7.10	6.48	6.20	6.12	6.20	7.27
	Mean LSD 05, 0.061	10.0	8.2	6.9	6.1	6.3	6.0	5.9	0.08[a]
EC ($\mu S\ m^{-1}$)	0–15	405	126	600	250	55	320	210	280.9
	15–30	545	137	600	225	37	209	230	283.3
	30–45	770	143	500	229	35	270	210	308.1
	45–60	980	147	400	221	35	270	220	324.7
	Mean LSD 05, 11.2	675	138.3	525	231.3	40.5	267.3	217.5	14.8[a]
OC ($g\ kg^{-1}$)	0–15	3.76	3.3	5.6	2	7.1	5.6	5.8	4.74
	15–30	1.34	3.5	4.5	1.4	6.8	5.3	5.4	4.03
	30–45	0.92	4.9	3.0	1.6	7.6	5.4	5.4	4.12
	45–60	0.75	5.8	1.6	1.3	7.2	5.5	5.6	3.96
	Mean LSD 05, 0.12	1.69	4.45	3.67	1.58	7.18	5.45	5.55	0.16[a]
Nav ($mg\ g^{-1}$)	0–15	119	25	83	19	158	90	100	84.9
	15–30	49	22	64	18	146	70	85	64.9
	30–45	29	23	56	20	132	80	80	60.0
	45–60	21	22	42	19.41	142	70	80	56.6
	Mean, LSD 05, 5.44	54.5	23	61.3	19.1	144.5	77.5	86.3	7.20[a]
Pav ($mg\ g^{-1}$)	0–15	22	19.67	2.38	14.63	3.6	80	65	29.6
	15–30	13	16.4	1.73	11.44	4.2	40	61	21.1
	30–45	12	15.07	1.08	10.12	6.2	30	54	18.4
	45–60	11	15.43	0.63	9.91	4.8	30	54	18.0
	Mean LSD 05, 3.00	14.5	16.7	1.46	11.5	4.7	45	58.5	5.18[a]
K ($mg\ g^{-1}$)	0–15	58	31	210	163.8	93	110	130	113.7
	15–30	46	38	190	128	69	120	125	102.3
	30–45	44	41	140	113	83	130	126	96.7
	45–60	51	38	107	111	77	110	126	88.6
	Mean LSD 05, 5.50	49.8	37	161.8	129	80.5	117.5	126.8	7.27[a]

LSD, least significant difference.
[a] LSD for depth; EC, electrical conductivity; OC, organic carbon; Nav, available nitrogen; Pav, available phosphorus; K, potassium.

of corresponding replicates. Analysis of variance (F test) was applied to examine the significance of differences among the treatments at all sites. Critical differences among the sites and treatments were determined using general linear model of SPSS software package SYSTAT-9.0′ version.

3. Results and discussion

3.1. *Effect of spacing on growth and seed yield*

There was no consistent pattern of increase or decrease in height with respect to spacing during five years and plant spacing did not affect significantly height at any location (Fig. 3A). Plant growth (height, branches and canopy spread) depends on the interaction between edaphic and climatic factors, in a highly ordered and organized way. As plant population increases per unit area, a point is reached where plants begin to compete for essential growth factors like nutrients, sunlight and water. In this study, the effect of decreasing competition due to wide spacing was smaller at all study sites. This indicates that increasing plant population density per unit area does not affect the growth of individual plants as plant population density at 2 × 2 m spacing is below the level at which competition occurs between plants. When we compared the height of plants amongst the different locations, it was greatest at Hyderabad and least at Lucknow and Naharlagun. Similarly, effect of spacing on number of branches was insignificant at all locations, though, maximum branches were recorded at 2 × 2 m spacing at Bhavnagar and Hyderabad (Fig. 3B). In general, all the growth parameters have been found superior at Hyderabad and Bhavnagar. Plant growth in north-east states was inferior to that of Jodhpur and Hyderabad sites despite the high organic carbon content in the soil, which indicates that even the good soil does not support much for its productivity at high rainfall in north-east states. In another study, effect of spacing (2–3 m wide) on growth characters was not found significant atleast for initial two years [13]. The recommended spacing for hedgerows or soil conservation is 15–25 cm apart (within and between rows) in one or two rows and 2–3 m by 1.5–3 m for block plantations [24]. Thus there will be 4000 to 6700 plants per kilometer for a single hedgerow and double that when two rows are planted. The number of plants per hectare at planting may range from 1100 to 3300. It was suggested that a high density plantation at 2 × 2 m spacing would be better to begin with the

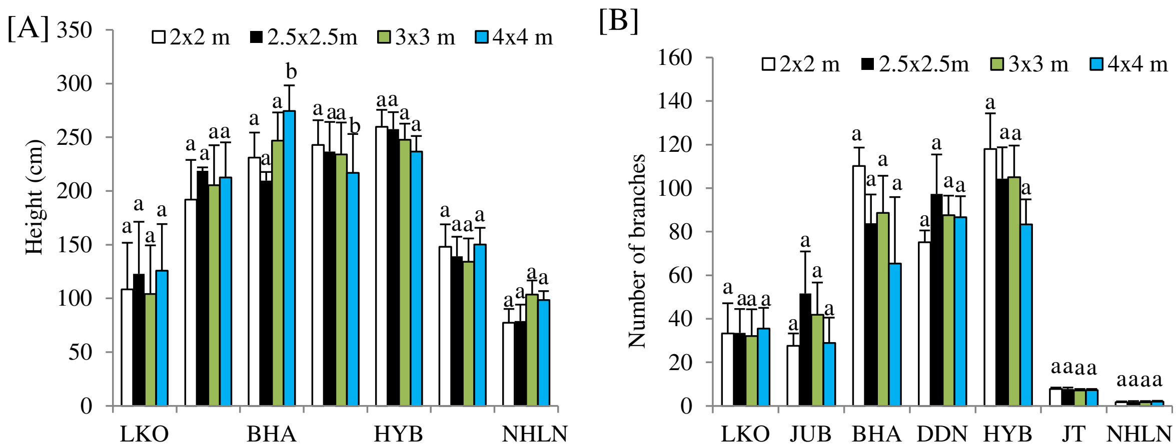

Fig. 3 – Effect of spacing on height [A] and number of branches [B] of *Jatropha* at different locations in India. Bar shows standard deviation. LKO = Lucknow, JUB = Jodhpur, BHA = Bhavnagar, DDN = Dehradun, HYB = Hyderabad, JT = Jorhat and NHLN = Naharlagun. Different lowercase letters indicate the significant differences between treatments at the same study site at $P < 0.05$.

block plantations in rainfed conditions, and gradually thinning or removing the rows or individuals of relatively weak performance may be more worthwhile [5].

Plants in spacing trial at Lucknow, Jodhpur and Naharlagun did not bear fruits in five years (Table 2). The observed data showed that the widest spacing gave the lowest seed yield. Seed yield obtained at four sites (Bhavnagar, Hyderabad, Dehradun and Jorhat) showed that increase in spacing from 2 × 2 m to 4 × 4 m led to decrease in seed yield per unit area by 70–80%. Heller [1] also found high yield of fruits of *Jatropha* at narrow spacing. Seed yield per unit area at five years growth was recorded maximum at 2 × 2 m spacing at Hyderabad. A narrow spacing will lead to fast canopy closure which results in higher water and light competition and lower fruit: biomass ratio in the mature stadium [13]. Seedlings of the 14 accessions of *Jatropha* were raised as a green hedge plantation with close spacing for screening of superior accessions on the basis of traits like general appearance, pest resistance, seed yield and seed oil content [25]. They found the four best accessions producing on the basis of one plant between 240 and 394 g of seed after attaining the plant height from 2 to 3 m. Behera et al. [13] proposed that when *Jatropha* is planted for live-fencing or hedges for soil conservation purpose, a dense biomass is needed and therefore close spacing is appropriate. However, when the aim of the plantation is to maximize seed yield, seedlings should be planted wide enough to ensure high seed yields in the mature stage, but close enough to avoid unacceptable loss of photosynthetic capacity in the juvenile stage. Thus, optimum spacing can be recommended only after minimum 5 years of continuous growth and yield observations and also in different environmental conditions and using different provenances. Our findings during five years suggest that plantation of *Jatropha* should be commenced with a spacing of 2 × 2 m and in due course of time alternate plants can be removed (thinning) when competition starts after five to ten years. In this study, such competitions have not been found yet during the last five years.

3.2. *Effect of pruning on growth and seed yield*

While technical aspects of oil processing of seeds of *Jatropha* are under intensive investigation, comparably little is known about the performance of *Jatropha* in the field [26]. Therefore in this study we have investigated the pruning induced differences on number of branches and seed yield. Number of branches decreased significantly with increasing pruning height from the ground at Jodhpur (Fig. 4), whereas at other sites effects of pruning were not significant. Conversely,

Table 2 – Seed yield (kg ha^{-1}) of *Jatropha curcas* in spacing trial at five year growth stage. Values are mean of five replicates.

Treatments	Study sites				
	Bhavnagar	Hyderabad	Dehradun	Jorhat	Naharlagun
2 m × 2 m	1440	326	208	447	88
2.5 m × 2.5 m	1089	216	142	232	0
3 m × 3 m	1004	173	114	68	0
4 m × 4 m	421	68	52	90	0
LSD 05	145	NS	NS	93.8	0

LSD = least significant difference, NS = not significant.

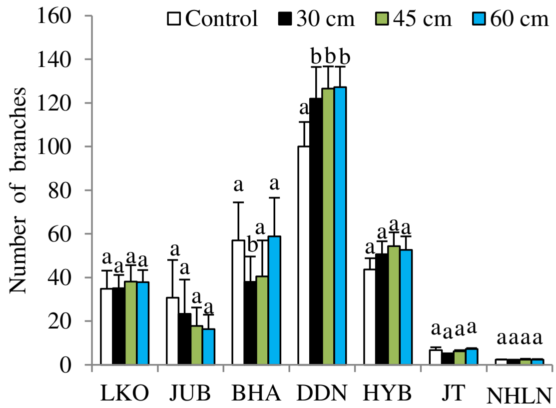

Fig. 4 – Effect of pruning on number of branches of *Jatropha* at different locations in India. Bar shows standard deviation. LKO = Lucknow, JUB = Jodhpur, BHA = Bhavnagar, DDN = Dehradun, HYB = Hyderabad, JT = Jorhat and NHLN = Naharlagun. Different lowercase letters indicate the significant differences between treatments at the same study site at $P < 0.05$.

pruning at the height of 30 cm from ground increased the growth and branches significantly among the treatments pruned at 15, 30, 45 cm height from the ground [13]. Pruning is an essential architectural intervention for optimizing the productivity in most of the bushy plants including *Jatropha* [27,28]. Rajaona et al. [26] studied the effect of different pruning types (shorter and longer lateral branches) on aboveground biomass, growth of twigs and leaves, dry mass allocation to branches, twigs and leaves, length of twigs per cm of branches and specific leaf area. They found aboveground biomass, growth of twigs and leaves were significantly affected with pruning types and other attributes of *Jatropha* were not affected by pruning types. Authors suggested that pruning should be considered as a management tool to optimize biomass production and seed yield and they were in favor of long term studies on effects of pruning on growth and yield attributes of *Jatropha*.

Recently, Everson et al. [10] have found significant increase in emergence of new branches and luxuriant growth with the effect of pruning in the two year old *Jatropha* plantation but increase in seed yield was not significant when compared to first year plantations. In present study pruning treatments did not affect significantly the seed yield at most of the locations, baring Hyderabad site where pruning at 45 cm produced significantly high yield in comparison to other treatments under trial at five years plant growth (Table 3). However, the unpruned treatment at Jorhat provided maximum yield. But there was no yield at all in pruned as well as un-pruned plants at Lucknow, Jodhpur and Naharlagun. Ghosh et al. [29] observed that although pruning has increased the number of secondary branches to about 30% over the unpruned *Jatropha*, but pruning caused a negative effect on fruit formation as the unpruned *Jatropha* produced significantly higher capsules in comparison to pruned plants. The practice of pruning from different locations of India showed that this treatment should be applied atleast after three years of initial establishment to increase branches, shorten tree height and increase fruit production which is still uncertain. However, in general, study revealed that pruning of the main branch at 30–45 cm height after three years of growth would be ideal for maximizing the growth rate and for optimizing the number of primary and secondary branches which may render relatively high seed yield.

Table 3 – Seed yield (kg ha^{-1}) of *Jatropha curcas* in pruning trial at five year growth stage. Values are mean of five replicates.

Treatments	Study sites			
	Bhavnagar	Hyderabad	Dehradun	Jorhat
Control	357	18.32	140.39	521.63
30 cm	178	34.18	107.89	0
45 cm	204	41.19	120.39	0
60 cm	283	36.04	120.79	0
LSD 05	119	12.18	NS	–

LSD = least significant difference, NS = not significant.

3.3. *Effect of irrigation on growth and seed yield*

Jatropha does not grow well under drought prone areas and requires atleast modest irrigation (monthly) during dry period. Effect of irrigation on height was insignificant at every site, except Lucknow, where irrigation at 15 days interval (I_1) increased height growth significantly (Fig. 5A) but number of branches could not which was significantly lower than life saving irrigation treatment (I_0) (Fig. 5B). However, number of branches was significantly higher in irrigated *Jatropha* plantation than non-irrigated at Jodhpur, Bhavnagar and Dehradun (Fig. 5B). In earlier studies different irrigation frequencies (7, 15, 30 days) were applied, but it did not give any significant difference on the plant growth performance [13]. Srivastava et al. [14] irrigated several accessions of *Jatropha* at 15 days intervals during summer throughout the study period (2005–2008) and observed significant differences amongst the accession. This indicates that irrigation frequency did not affect *Jatropha* growth significantly.

The relationship between irrigation frequency and the seed yield of *Jatropha* was not identical amongst the sites under study (Table 4). There was no fruiting on the two sites i.e., Lucknow at all the irrigation frequencies and I_0 and I_1 levels at Jodhpur even after five year of plant growth. Irrigation after 30 days (I_2) intervals was relatively superior to enhance seed yield significantly by 24% at Bhavnagar, but at Dehradun irrigation after 60 days (I_4) led to increase seed yield by 21% though it was statistically not significant (Table 4). In an earlier study *Jatropha* plants were irrigated by different water amounts at 125%, 100%, 75% and 50%, of the potential evapotranspiration (ETp), in which the highest seed yield was recorded at 100% of ETp (195.08 kg ha^{-1}) the minimum value of the seed yield (90.42 kg ha^{-1}) was recorded with 50% of ETp [17]. One of the major reasons for selection of *Jatropha* as a biofuel resource is so called low water requirement which cannot be certified for dry land farming (unirrigated) in dry and arid regions. As such optimum irrigation at 30–45 days interval is recommended for fruitful production.

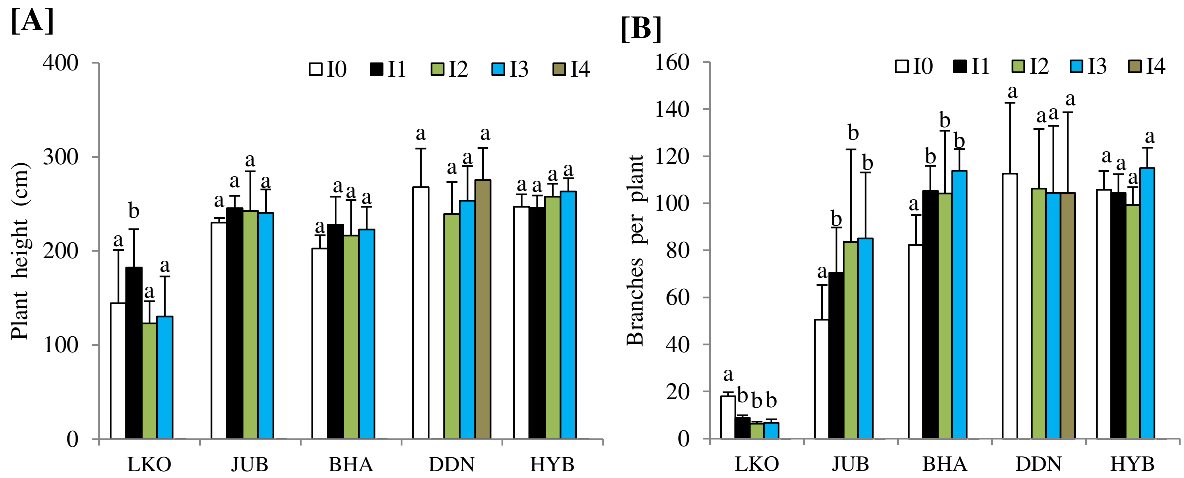

Fig. 5 – Effect of irrigation on height [A] and number of branches [B] of *Jatropha* at different locations in India. Bar shows standard deviation. LKO = Lucknow, JUB = Jodhpur, BHA = Bhavnagar, DDN = Dehradun, HYB = Hyderabad, JT = Jorhat and NHLN = Naharlagun. I_0 = No irrigation, I_1 = 15 days interval, I_2 = 30 days interval, I_3 = 45 days interval and I_4 = 60 days interval. Different lowercase letters indicate the significant differences between treatments at the same study site at $P < 0.05$.

3.4. *Effect of fertilizer on growth and seed yield*

Effect of fertilizer on height and branches was not significant at all the study sites (Fig. 6A, B), though the height and branches, both were relatively good at Dehradun, Bhavnagar and Hyderabad. *Jatropha* attained the maximum average height 258 cm at Dehradun (DDN) and minimum 76 cm at Naharlagun (NHLN). FYM treatment (F_2) was superior at Lucknow, chemical fertilizers (F_3) at Jodhpur and a combination of FYM and chemical fertilizers (F_4) produced good result at Dehradun, Hyderabad and Jorhat sites, while it was significant at Jorhat only (Fig. 6A). Alike to height, effect of fertilizers on number of branches was insignificant at all the sites (Fig. 6B). A recent study on the impact of organic amendment on early growth performance of *Jatropha* on a severely degraded site reported that with direct seeding, 20% of the plants treated with organic manure survived after 2 years, while all seedlings of the control plot perished. In the plantations, 30% of the untreated seedlings remained alive and only 5% of the plants survived with amendment [30]. It was reasoned that organic amendment attracted humivorous termites, which were destructive to the seedlings. The low survival rates (5–30%) and meagre seedling performance, even for the amended plots, may be an indication that *Jatropha* is unsuited to severely degraded lands and cannot be expected to give good yields and the claimed environmental and socio-economic benefits. This is important to note that in cases where cultivation of *Jatropha* is to be undertaken on marginal lands there should be little or no variable (chemical, organic and bio fertilizers) inputs unless the plant is properly domesticated as high yielding crop alike to that of annual crops for fetching a good turnover. Here efforts of plant breeders and agronomists need to be strengthened in this direction.

Table 4 – Seed yield (kg ha^{-1}) of *Jatropha curcas* in irrigation trial at five year growth stage. Values are mean of four replicates.

Treatments	Study sites			
	Jodhpur	Bhavnagar	Hyderabad	Dehradun
I_0 (no irrigation)	0	858.3	69.41	189.46
I_1 (15 days Interval)	0	921.1	92.39	NT
I_2 (30 days Interval)	118.72	1130	92.40	165.06
I_3 (45 days Interval)	64.24	960.9	92.42	230.69
I_4 (60 days Interval)	NT	NT	NT	238.46
LSD 05	23.2	107.1	NS	NS

LSD = least significant difference, NS = not significant, NT = no treatment.

Seed yield was poor at most of locations (Jodhpur, Hyderabad, Dehradun, Jorhat, and Naharlagun) and maximum yield (1.09 kg ha^{-1}) was recorded at Bhavnagar in F_4 treatment (Table 5). There was no yield at Lucknow. Since *Jatropha* is recommended for plantation on degraded wastelands, plants respond better to organic manure in comparison to chemical fertilizers [8,31]. However, in this study a combination of farm yard manure and chemical fertilizer has produced significantly higher seed yield than the other treatments at most of the locations excluding Jodhpur. *Jatropha* has also been reported to develop a symbiosis with the root fungus, mycorrhiza, which might result in increased efficiency in assimilating otherwise unavailable nutrients, particularly phosphate. Application of bio-fertilizers (VAM cultures) and various seed cakes were also tried in which *Jatropha* cake was superior as compared to *Pongamia* and Neem cake during two years growth assessment [13]. This may be possible due to high N (3.83%) P (1.75%) and K (1.44%) content in the seed cake of

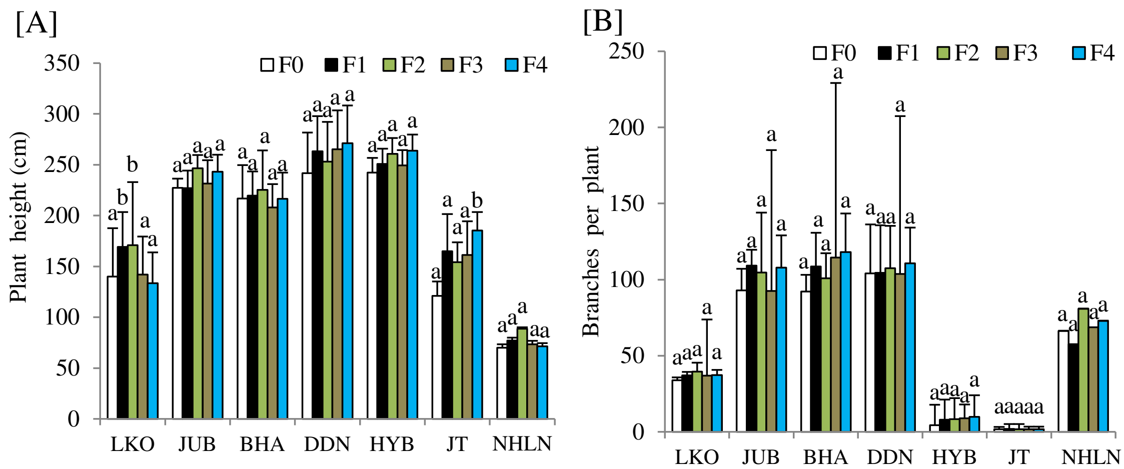

Fig. 6 – Effect of fertilizer on height [A] and number of branches [B] of *Jatropha* at different locations in India. Bar shows standard deviation. LKO = Lucknow, JUB = Jodhpur, BHA = Bhavnagar, DDN = Dehradun, HYB = Hyderabad, JT = Jorhat and NHLN = Naharlagun. F_0 = no organic manure i.e. FYM, F_1 = 2 kg FYM, F_2 = 5 kg FYM, F_3 = Nitrogen 10 g + P 20 g, K 10 g, F_4 = 2 kg FYM + Nitrogen 10 g + P 20 g + K 10 g. Different lowercase letters indicate the significant differences between treatments at the same study site at $P < 0.05$.

Jatropha [24]. Application of *Jatropha* seed cake is important in the view of recycling of the major part of the available nutrients to maintain soil fertility of infertile marginal lands. The presence of bio-degradable toxins, mainly phorbol esters in the *Jatropha* seed cake serves as bio-pesticides/insecticides and molluscicides [8,32]. Mohapatra and Panda [33] demonstrated that application of 60 g N to each plant would be beneficial for enhanced yield of a five-year old standing crop under tropical agroclimatic condition in an Aeric Tropaquept soil type. The seed yield obtained in various field experiments including this study is inconsistent with the figure reported in the literature [5,8], where 4–5 t ha^{-1} seed is expected as a reliable yield estimate for a well managed plantation in good environmental conditions [15]. Unfortunately, such expectation could not be verified till date in India, probably due to poor site conditions and lack of a high yielding domesticated variety. Therefore, its extension on large scale is questioned in India, unless the economic yield is ensured.

Unlike to the presumptions for disease resistance, *J. curcas* is susceptible to many insects, pests and viral diseases such as root rots, stem borer, fruit damage by Webber at Hyderabad (Fig. 7A, B) and plant damaged by root rot and fruit Webber at Lucknow (Fig. 7C, D). The fruit sap suckers [34,35], virus infestation (Lucknow), and bark eater rodents (Jodhpur) are quite common problems at different locations. The major problems reported are caused by the scutellarid bug *Scutellera nobilis* Fabr., the capsule borer *Pempelia morosalis* Saalm and Uller, *Pachycoris klugii* Burmeister (Scutelleridae), *Leptoglossus zonatus* Dallas (Coreidae), the blister miner *Stomphastis thraustica* Meyrick (Acrocercops), the semi-looper *Achaea janata* L., and the flower beetle *Oxycetonia versicolor* Fabr [36–38]. As the *Jatropha* plantations are spreading fast, incidence of such risk cannot be ruled out in India [34] and other tropical countries [10].

The appropriate edaphic and climatic conditions for the cultivation of *Jatropha* are summarized in Table 6. Hot and humid climate is more suitable for the emergence of *Jatropha* seeds. Therefore, fairly warm summers with rains are beneficial for proper germination of seeds. The flowering is initiated in rainy season with reduction in temperature and plants

Table 5 – Seed yield (kg ha^{-1}) of *Jatropha curcas* in fertilizer trial at five year growth stage. Values are mean of four replicates.

Treatments	Study sites					
	Jodhpur	Bhavnagar	Hyderabad	Dehradun	Jorhat	Naharlagun
F_0 (no FYM)	5.12	922	58.65	183.96	108.87	57.66
F_1 (2 kg FYM/Pit)	51.36	984	84.58	186.80	454.81	111.61
F_2 (5 kg FYM/Pit)	–	1055	76.98	211.49	114.94	83.37
F_3 (N10 g + P20 g + K10 g/Pit)	7.76	787	88.40	193.86	393.41	102.67
F_4 (2 kg FYM + N10 g + P20 g + K10 g/Pit)	3.2	1088	124.70	244.80	535.30	150.14
LSD 05	–	49.5	NS	NS	76.64	66.35

LSD = least significant difference, NS = not significant.

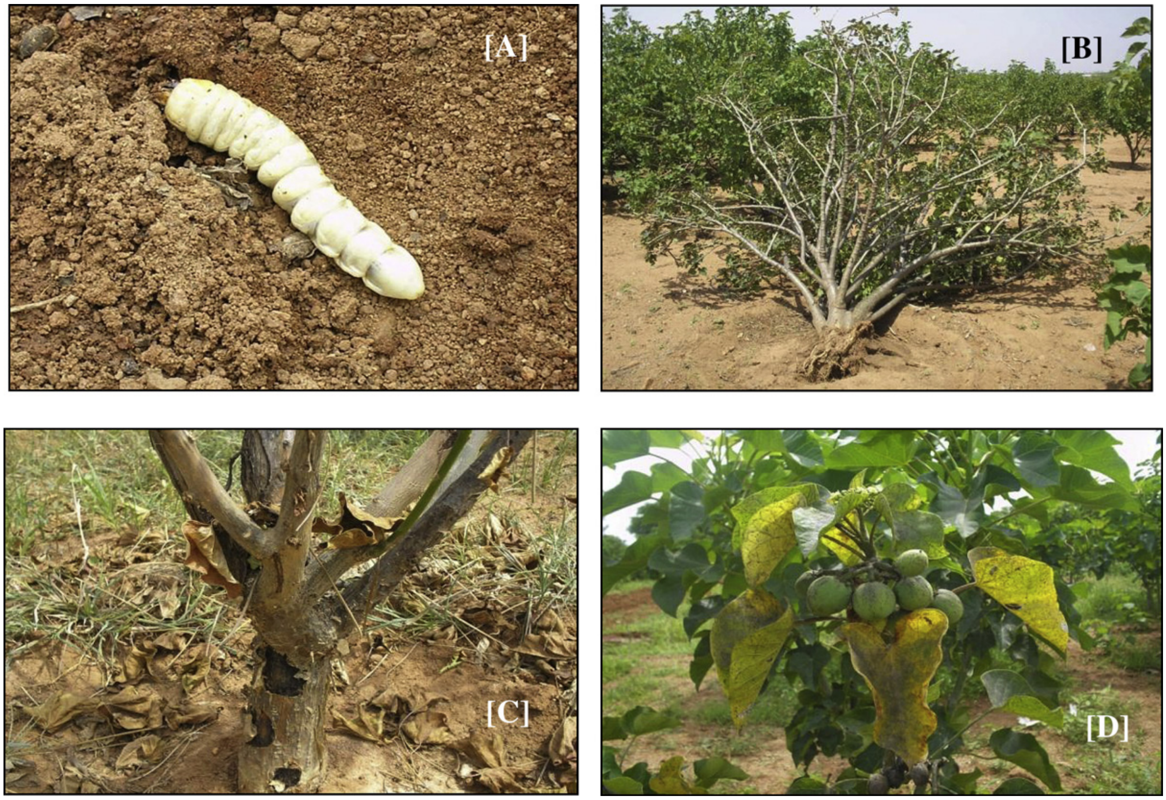

Fig. 7 – Disease incidence and plant damage at study sites. Stem borer [A], plant damaged by stem borer [B] hole symptoms at Hyderabad, [C] plant damaged by root rot and fruit Webber [D].

bear fruits in winter. As stated earlier that *Jatropha* can be cultivated with success in areas with scanty to heavy rainfall 200–1500 mm year^{-1} [39] and without irrigation in a broad spectrum of rainfall regimes, from 250 to 3000 mm per annum [40], does not find a place in Indian situations, where ≈700–800 mm annual rainfall appears to be optimum. Above this threshold fungal diseases may affect the plants [41] and below the range irrigation would be essential in summer.

Table 6 – Appropriate conditions suitable for cultivation of *Jatropha* at a glance.

Factors	Suitable limit		
	Current observations	Reported earlier	References
Temperature	26–28 °C	18–40 °C	[27]
Rainfall	400–1000 mm	250–1000 mm	[27]
Altitude	<400 m	Low < 500 m	[28]
Soils	Well drained, porous, low bulk density, saline & sodic not suitable, thrives well even at 20 cm soil depth in Gujarat	Grows on wide range of soils including degraded land, saline & sandy soils, needs soil depth atleast 45 cm	[27,44]
Frost	Sensitive (Dehradun)	Sensitive	[27]
Drought	Tolerant	Withstand long period	[45]
Shade	Sensitive	Sensitive	[45]
Water logging/flood	Highly sensitive to water logging (Lucknow) and floods (Manipur)	Does not grow in wetlands	[28]
Nutrients	Grows well in poor soils of low fertility, responds better to FYM than NPK fertilizer, VAM beneficial, although yield potential is poor, needs development of high yielding variety	Can thrive on low fertility soils, requires NPK for optimum growth, better to organic manure than mineral fertilizer. Mycorrhizal associations increase phosphorous availability and water uptake	[27] [8] [14] [45]
Pest and disease	Many diseases like virus, stem/capsule borer, sap suckers root rot, fruit Webbers and bark eaters were noticed	No major pest and diseases	[27]

The temperature range of 18–40 °C appears to be suitable for *Jatropha* cultivation, which occurs in most parts of the country. Frost-prone areas are not suitable for *Jatropha* cultivation [27]. We have noticed considerable frost damage at Dehradun site in our study.

4. Conclusions

Various reports, proceedings, expectations and assumptions anticipate the yield of *Jatropha* varies from 0.2 kg to >2 kg seeds from a single plant or 2–5 t ha^{-1} and even 7.8 to 12 t ha^{-1} [5,8,23,42]. However, seed yield in the present study is far below from such expectations. Collating the growth data of different locations with rainfall, temperature and humidity it is concluded that the growth of *J. curcas* was relatively good in low rainfall zones where humidity remains less throughout the year but a high temperature prevails for a quite long time in a yearly cycle. Thus the interaction of plants with soil and climate indicates that no single agricultural prescriptions can be recommended for all sorts of degraded lands and that even with the optima found on some of the trial sites; the yields were substantially lower than would be necessary for an economic crop. Gujarat (Bhavnagar) and Andhra Pradesh (Hyderabad) appear as potential states for its extension in comparison to other regions like Uttar Pradesh (Lucknow), Uttrakhand (Dehradun) and North–East States. Although, we could not get a reasonable yield at Jodhpur (Rajasthan) due to biotic disturbance mainly rodents attack, but Rajasthan Forest Corporation supplies bulk of seeds to several companies and institutions in India. A few limitations cannot be undermined for its extension such as in Tamilnadu, the crop impoverishes farmers, particularly the poorer and socially backward farmers, where *Jatropha* cultivation not only failed to alleviate poverty, but its aggressive and misguided promotion will generate conflict between the state and the farmers, between different socio-economic classes and even within households [43].

As *Jatropha* is still a wild plant, careful selection and improvement of suitable germplasm is necessary before massive plantation on a large scale, especially on farmer's land. Comprehensive research and experimentation is still required to develop a high yielding annual variety for *Jatropha* based biodiesel production and long-term productivity assessment is required in different climatic and edaphic conditions. It would be a good practice to inoculate cuttings with mycorrhizal fungi when establishing them into nursery. This treatment improves the quality of the plant-fungal symbiosis in the field conditions especially in soil with poor fertility, as endo-mycorrhizal fungi were demonstrated to be commonly found in association with *Jatropha* in natural conditions. It should be planted in the refilled holes of 45 cm^3 size duly amended with the soil, compost manure or local soil amenders. The plants of 50 cm height and/or six month age are suitable for plantations on degraded soil sites. The best time for planting is in the rainy season before or at the onset of the rains. Direct seed sowing under field conditions is not advised as it leads to poor germination and high mortality of the seedlings under suboptimal/marginal conditions. We recommend 3 × 3 m optimum spacing for block plantations and no pruning for three years. Initial soil amendments are preferred on degraded lands (2 kg of organic manure and nitrogen, phosphorous and potassium at 10 g, 20 g, and 10 g, respectively) for a good population establishment. An optimum irrigation at 30 days interval during March and April and 15 days in May and June would reasonable. During normal rainfall, no irrigation is required in monsoon season (July to September) and occasional in winter season as it remains dormant in winter. Sodic soils of high pH and bulk density are not suitable for cultivation *Jatropha*.

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