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Climate and soil-site suitability criteria for *Jatropha curcas* L. cultivation under non-arable marginal lands in different agro-ecological regions of India

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Abstract

In recent years, much emphasis has been given for biodiesel fuel production through different biofuel crops, particularly *Jatropha curcas* (*J.curcas*) targeting degraded or waste lands and marginal lands that are unsuitable to agriculture. However, public and private investments for *J.curcas* cultivation were not sufficiently based on scientific knowledge of climate and soil-site requirements. An attempt is made in this paper to develop climate and soil-site suitability criteria for efficiently growing *J.curcas* in non-agricultural lands. Information was compiled on selective climate and soil-site parameters and performance of *J.curcas* from natural distribution and some locations of *J.curcas* cultivation from 99 agro-ecologically diverse districts. The climate and soil-site requirements of *J.curcas* were derived based on which high, moderate and marginal suitability of *J.curcas* was identified. The climate suitability criteria were based on mean annual rainfall (mm), maximum and minimum temperature (°C) and length of growing period (days). The soil-site suitability criteria was based on altitude, slope (%), drainage, proneness to flooding/water logging, soil depth, texture, sub- soil gravelliness (%) and soil reaction (pH). The criteria were used to assess marginal lands for Jatropha suitability in Andhra Pradesh. The assessment showed a significant positive correlation with crop performance under highly suitable, moderately suitable and marginally suitable lands. The criteria developed could be adopted for delineating suitable areas for *J. curcas* plantation in non- arable lands under similar soil and agro-climatic conditions.

Keywords: Climate suitability, Correlation, *Jatropha curcas*, Marginal lands, Soil-site suitability

Introduction

There is a considerable interest in biofuels aiming to reduce dependence on fossil fuels, due to climate change issues aiming to reduce CO_2 emissions, apart from geo-political issues (Verrastro, 2007). However, the focus of biofuel production is on marginal and degraded lands under arid and semi-arid regions, without competing for food production or depleting natural carbon stocks and ecosystem services. The competition by biofuel crops for water with other annual crops and economic activities will increase due to high water footprint (De Fraiture. *et al*., 2009). At a global scale, research studies indicated use of marginal or 'abandoned' crop lands for biofuel crops to avoid competition with food crops (Tilman *et al*., 2009). Recently, *Jatropha curcas* attracted attention of research organizations, governments, public and international development agencies and industries in tropics and sub-tropics due to wider adaptability as a diesel fuel substitute (GEXSI, 2008) with multiple benefits like alleviation of soil degradation, desertification and deforestation, climatic protection etc. The Indian National Biofuel Policy (GOI, 2009) aims at blending 20% bio-ethanol and biodiesel with gasoline and diesel, respectively by 2017. The Indian approach to biofuels is focuses on not to conflict with food security and non-food feed stocks being raised on marginal or waste lands thus, avoiding a possible conflict of fuel and food security. The target is to be met through cultivation of 13.4 m ha of 'wasteland' precisely with *J. curcas*. Each species would require specific climate and soil-site conditions for optimum growth at different stages. Agro-ecological settings of *J.curcas* growing regions are well spread in India. However, there are specific climate and soil-site conditions that would influence its adaptation and production. Considering the importance attached to *J. curcas* for promotion of biofuel crops in India, an attempt is made in this paper to develop climate and soil-site suitability criteria for growing *J. curcas*.

Materials and Methods

Selection of study area: The study locations are in 99 districts in 24 states in India which fairly represent diverse climates, site conditions and soil types, where majority of *J.curcas* existed in its natural area of distribution and some areas under its plantation. The locations included one district in arid zone *viz*., Hisar; 23 districts in dry semi-arid zone (500-750 mm) *viz*., Mahendrgarh, Rajasamand, Anantapur, Gurgaon, Ahmednagar, Rohtak, Bhavnagar, Udaipur, Rajkot, Bijapur, Bellary, Surendranagar, Sirohi, Solapur, Banaskantha, Ludhiana, Bhilwara, Coimbatore, Jalandhar, Dungarpur, Belgaum, Nalgonda and Mahbubnagar; 24 districts in moist semi-arid zone (750 -1000 mm) *viz*., Jalna, Aurangabad, Chiittorgarh, Prakasham, Akola, Hamirpur, Junagadh, Ranga Reddy, Bangalore (rural), Chittioor, Osmanabad, Kanpur, Jabhua, Dhar, Guntur, Ujjain, Parbhani, Allahabad, Navanshahr, Lucknow, Indore, Raibareily, Warangal and Nellore; 16 districts in dry sub-humid zone (1000-1200 mm) namely Gurdaspur, Shahjapur, Panchamahal, Chattarpur, Dewas, Satna, Khammam, Adilabad, Visakhapatnam, Pune, East Godavari, Rewa, Vizianagaram, Srikakulam, Sidhi and Almora; 14 districts in moist sub-humid zone (1200-1600 mm) *viz*., Shahdhol, Gorakhpur, Purulia, Ganjam, Bankura, Bardhman, Imphal, Golaghat, Ranchi, Bilaspur, Khodra, Jagdalpur, Pauri Garwal and Shimla; 14 districts in humid zone (1600-2500 mm) *viz*., Midnapur, Kabri Anglong, Phulbani, Nilgiris, Baleshwar, Nainital, Pittorgarh, Sonitpur, Dehradun, West Tripura, Tiswali, Palakkad, Mon and Mokokchung) and 7 districts in per-humid (>2500 mm) *viz*., West Garo Hills, Lakhimpur, Perenem I,Dharmashala, Bongaigaon, Papumpare and Dibong Valley.

Information on specific climate parameters was compiled from State Agricultural Universities, network centers of All India Coordinated Research Project on Agro-meteorology, AICRP for Dryland Agriculture and other secondary sources. Information on length of growing period (LGP) was adopted from Mandal *et al*. (1991). Details of soils and site characteristics of locations in 99 districts were compiled from 392 soil mapping units from Soil Resource Information Reports of respective states developed by National Bureau of Soil Survey and Land Use Planning. Observations on growth and yield performance of J.curcas at different growth stages *viz*., vegetative, flowering and fruiting stages were collected from *J. curcas* sites, SAUs, AICRPDA centres, and other secondary sources.

For site and soil parameters, scores were assigned for studying relationship of these parameters with performance of *J. curcas*. For site parameters a) slope: 1= rolling lands/ steeply or moderately steeply sloping lands/ hills and ridges, 2= gently sloping/undulating land, 3= flat lands/nearly level/very gently sloping; b) drainage: 1= poorly drained/imperfectly drained, 2= moderately well drained/ excessively drained, 3 = well drained; c) flooding: 1= moderately flooding, 2 = slight flooding (<days), 3 = no flooding (3-6 days). For soil parameters a) soil depth:1= very shallow/ extremely shallow, 2 = shallow, 3 = moderately shallow, 4= moderately deep/ medium deep and 5= deep and very deep; b) soil texture: 1= sandy/ clayey (smectitic), 2= loamy sand/clay (mixed), 3=silt loam/ clay loam/sandy clay loam/sandy loam, and 4= loamy; c) sub-soil gravelliness: 1= >50, 2= 35-50, and 3= <35; pH:1=4.0 to 4.5 and 8.0 to 9.5, 2= 5.0 to 5.9 and 7.1 to 7.9 and 3 = 6 to 7. For *J. curcas* performance: 1= poor, 2 = medium, and 3= good. The scores were combined for climate and soil site parameters for each district. They were cumulated and arranged in descending order of total value of scores.

District wise data on performance of *J. curcas*, climate and soil site parameters were analyzed for relationship between different parameters and significance both under climate groups and pooled over different climates based on relationship among different parameters. Multiple regression models were calibrated to predict *J. curcas* yield through climate and soil site parameters under each climate and were pooled over different climatic zones. The performance of *J. curcas* for seed yield was assessed based on (i) coefficient of determination (R^2) which indicates seed yield predictability (ii) standard error of seed yield and (iii) significance of parameters in models (Gomez and Gomez, 1984). Based on score values of parameters, the performance of *J.curcas* was assessed.

Different climatic and soil-site parameters were studied and prioritized. The most relevant parameters were considered for setting criteria for suitability of *J. curcas*. Using data collected on parameters from 99 districts in 24 states in India, climate and soil-site suitability criteria was developed for *J. curcas* based on FAO guidelines (FAO, 1996). The criterion was validated for marginal lands in Andhra Pradesh. The performance of *J. curcas* based on passport data provided by National Bureau of Plant Genetic Resources, Hyderabad in respect of poor, medium and good were verified with climate and soil-site suitability criteria.

Results and Discussion

Relationship between climate parameters and performance of *J. curcas*: The rainfall and yield related parameters (mean of districts in each climate zone) along with descriptive statistics is given in table 1. At maximum locations under dry semi-arid zone, *J. curcas* performed better between 600-700 mm, compared to moist semi-arid zone between 800-850 mm and under dry sub-humid zone between 1100 -1150 mm. The performance of *J. curcas* was medium under sub-humid zone between 1250 and 1400 mm and under humid zone around 1700 mm. Based on relationship of yield and rainfall data pooled over climate zones, moderate to high seed yield of Jatropha was attainable under about 600 to 1500 mm (Fig. 1). *J.curcas* prefers warm season for planting as it is sensitive to ground frost during cold season. Hot and humid weather is preferred for good germination of seed. The species would take about 3 to 5 years for providing seed yield based on soil and rainfall conditions. In general, the performance of *J. curcas* was poor to moderate under low rainfall areas (less than 1000 mm), while it performed better under high rainfall locations (more than 1000 mm). This was observed based on its performance during vegetative, flowering and fruiting stages without keeping other biophysical parameters as constraints. The production of *J. curcas* in locations with more than 1000 mm rainfall was better compared to areas which received less than 1000 mm indicating moderate suitability of *J. curcas* plantation. This clearly indicated that plantations under arid and semi-arid regions would need irrigation for better performance (Maes *et al.* 2009). Based on above observations, the suitability criteria for J.curcas with regard to mean rainfall was considered more than 1000 mm for high suitability, 600 to 1000 mm for moderate suitability and 500 to 600 mm for marginal suitability.

Based on relationship between annual maximum temperature and seed yield, locations had maximum temperature (Tmax) of 16.7 to 45 °C over different climate zones whereas, Tmax of 30 to 35 °C was optimal for attaining maximum yield under dry semi-arid zone, while it was 31 to 34 °C under moist semi-arid zone and dry sub-humid zones and 28 to 35 °C under moist sub-humid zone (Fig. 1). However, for attaining moderate to good yield, ideal maximum temperature could range between 18 to 38 °C. High temperature of beyond 36 °C during flowering was one of the major limitations for poor fruit setting and low yield. The suitability criteria for *J. curcas* with regard to mean annual maximum temperature could be considered as 28 to 36 °C for high suitability, 36 to 42 °C for moderate suitability and more than 42 °C for marginal suitability for adoption in different locations.

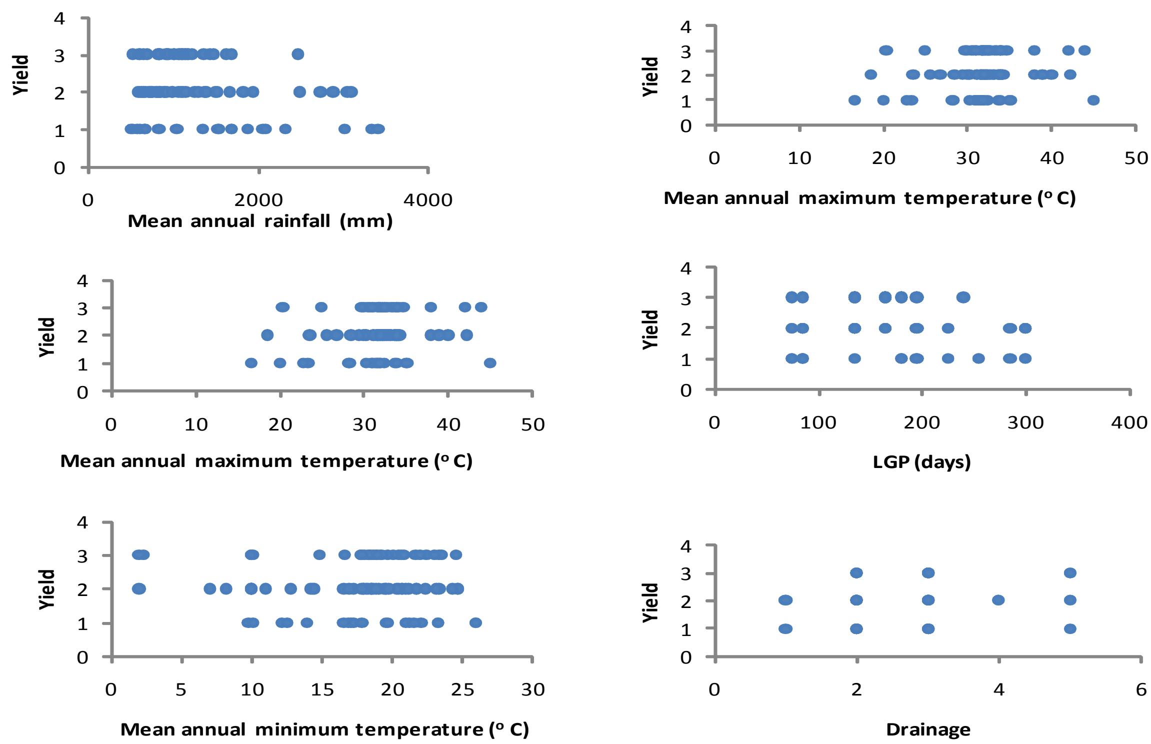

Fig 1. Relationship between mean annual rainfall (mm); mean annual maximum temperature (°C); mean annual minimum temperature (°C); length of growing of period (days); slope (%); drainage and seed yield of *Jatropha curcus*

The frost damage was observed in sites of *J. curcas* when exposed to frost beyond 24 hours. *J. curcas* recovered from slight frost damage, while plants could not recover from severe frost damage occurred for more than 3 days. Although it has capacity to recover from slight frost but seed production would be affected and plants would die after severe frost Sahoo *et al*., 2009. Generally, there are two flushes of flowering in *J. curcas i.e.*, in August-September (south-west monsoon) and March - May (summer). The favorable temperature required is about 20 to 28 °C. The species could withstand severe heat and also do well in slightly cool condition. It could withstand a slight frost but not for prolonged periods. Therefore, temperature during flowering is an important factor which affects the fruit set and seed yield under different zones. Further, the suitability criteria with regard to temperature during flowering was < 36 °C for high suitability, 36 to 42 °C for moderate suitability and > 42 °C for marginal suitability.

Length of growing period and performance: In some locations where LGP was more than 180 days, the performance was poor to moderate due to limitations of temperature (mean maximum and minimum temperature at flowering and fruit development stages) and soil (rooting depth, chemical or fertility) or, site characteristics (proneness to flooding and pH). High rainfall in relatively cooler parts did not encourage a vigorous growth of *J.curcas*. Further, excess rain and relative humidity attracted fungus which affected the seed yield. Based on relationship of LGP with seed yield, moderate to good yields were attained in different locations with LGP in the range of 120 to 300 days in different locations (Fig. 1). The suitability criterion for *J.curcas* with regard to LGP was considered as high suitability, 120 to 180 days for moderate suitability and 90 to 120 days for marginal suitability.

Site characteristics and performance

Slope (%) and performance: In higher altitudes, the performance of *J. curcas* varied from poor to moderate (Table 1). This could be ascribed to unfavourable conditions with respect to temperature and frost at growth and reproductive stages. Further, this may also be due to influence of

Table 1. Observations (mean of districts) on climate, site and soil parameters and performance of *Jatropha curcas* across climate zones

Districts	Climate parameters				Site parameters	
	MARF (mm)	Tmax (°C)	T min (°C)	LGP (days)	Slope (%)	Drainage
Dry semi arid zone (500-750 mm) (23 districts)						
Min	501.9	25.6	10.0	75	1	1
Max	749.0	44.0	22.5	135	3	3
Mean	643.7	33.1	18.3	88.9	2.3	2.2
CV (%)	10.7	10.6	16.2	21.1	35.8	37.1
Moist semi arid zone (750 -1000 mm) (24 districts)						
Min	752.2	29.5	2.3	85	1	2
Max	999.2	39.0	24.7	180	3	3
Mean	871.6	32.7	18.8	130.6	2.5	2.4
CV (%)	7.5	5.7	24.0	15.2	25.9	20.8
Dry sub humid zone (1000-1200 mm) (16 districts)						
Min	1012.2	20.4	7.1	135	1	2
Max	1179.6	45.0	24.6	195	3	3
Mean	1103.9	32.8	18.6	167.8	2.3	2.5
CV (%)	4.7	16.0	27.2	10.4	25.7	20.7
Moist sub humid zone (1200-1600 mm) (14 districts)						
Min	1226.3	16.7	9.8	165	1	2
Max	1539.3	42.0	22.1	300	3	3
Mean	1406.9	31.1	16.2	206.8	2.0	2.7
CV (%)	7.2	19.2	30.2	23.8	39.2	17.3
Humid zone (1600-2500 mm) (14 districts)						
Min	1626.8	18.6	2.0	165	1	2
Max	2500.0	38.0	26.0	300	3	3
Mean	2002.3	29.3	13.9	230.4	1.9	2.5
CV (%)	16.5	19.2	55.7	22.9	37.9	20.8
Per humid zone (>2500 mm) (7 districts)						
Min	2746.0	23.6	10.0	225	1	2
Max	3418.8	39.0	26.0	300	3	3
Mean	3085.1	31.9	17.9	278.6	1.9	2.3
SD	237.6	5.3	6.6	28.5	0.9	0.5
CV (%)	7.7	16.6	36.9	10.2	48.4	21.3

Districts	Soil parameters				Performance of *J. curcas*			
	Depth (cm)	Texture	pH	Total score	VS	FLS	FRS	Seed yield
Dry semi arid zone (500-750 mm) (23 districts)								
Min	1	1	1	11	1	2	1	1
Max	5	4	2	23	3	3	3	3
Mean	3.1	2.5	1.9	16.9	2.4	2.7	2.2	2.0
CV (%)	46.5	46.9	18.4	21.0	27.4	18.4	26.5	36.1
Moist semi arid zone (750 -1000 mm) (24 districts)								
Min	1	1	2	11	2	2	2	1
Max	5	4	3	23	3	3	3	3
Mean	3.1	2.5	2.1	17.6	2.6	2.8	2.5	2.3
CV (%)	54.0	40.9	13.6	19.2	18.8	14.9	20.4	24.2
Dry sub humid zone (1000-1200 mm) (16 districts)								
Min	1	1	2	12	2	1	1	1
Max	5	4	3	22	3	3	3	3
Mean	3.8	2.6	2.2	18.5	2.6	2.6	2.2	2.6
CV (%)	38.3	47.9	18.4	15.5	20.0	23.6	29.9	23.6
Moist sub humid zone (1200-1600 mm) (14 districts)								
Min	1	1	1	14	1	1	1	1
Max	5	4	2	22	3	3	3	3
Mean	3.5	2.5	1.9	17.6	2.6	2.6	2.2	2.1
CV (%)	35.0	43.7	19.6	16.1	25.1	24.0	26.1	35.2
Humid zone (1600-2500 mm) (14 districts)								
Min	2	1	1	11	2	2	1	1
Max	5	4	2	22	3	3	3	3
Mean	3.7	1.9	1.7	16.4	2.6	2.5	2.1	1.8
CV (%)	26.8	51.7	27.3	20.8	20.0	20.8	35.9	44.9
Per humid zone (>2500 mm) (7 districts)								
Min	3	1	1	15	2	2	1	1
Max	5	4	2	21	3	3	3	2
Mean	4.3	2.3	1.6	16.7	2.4	2.3	2.0	1.6
SD	0.8	1.3	0.5	2.4	0.5	0.5	0.6	0.5
CV (%)	17.6	54.8	34.0	14.1	22.0	21.3	28.9	34.0

MARF- Mean annual rainfall (mm); Tmax- Mean annual maximum temperature (OC); T min- Mean annual minimum temperature (OC); LGP- Length of growing period (days); VS- Vegetative stage; FLS- Flowering stage; FRS- Fruiting stage

other land qualities viz. LGP, soil type with varying physical and chemical properties (particularly rooting depth, texture, soil pH and organic carbon). However, lower slopes (< 5%) would be highly suitable for *J.curcas* based on performance observed at different locations. *J.curcas*, being a wild growing hardy plant, can be grown potentially over degraded lands which require revegetation, soil conservation and sand dune stabilization. The suitability criterion for *J. curcas* with regard to slope (%) was considered as category 3 for high suitability, category 2 for moderate suitability and category 1 for marginal suitability.

Drainage and performance: Drainage is an important land quality indicator that influences the growth, performance and yield of *J. curcas* as it prefers deep and well drained soils with good aeration (Openshaw, 2000), which allows for a strong vertical tap root development. Across climate zones, the performance was moderate to good in locations with well drained conditions and poor in locations with poor to imperfectly drained conditions (Table 1). However, drainage was better related to soil properties, particularly texture, structure and sub-soil garvelliness. The performance was invariably good in well drained soils compared to poor or imperfectly drained soils as observed in some sites with Vertisols and associated soils. Further, *J. curcas* was sensitive to flood condition in the field and failed under waterlogged areas. Highly fertile black cotton soils which could hold more water are not good for *J. curcas* plantation. Clay soils (Typic Vertisols) are unsuitable for *J. curcas*, if water logging or saturation occurs due to climatic conditions. Flooding or waterlogged condition beyond 3 days would be detrimental for growth and survival of *J. curcas*. Hence, locations with no flooding or waterlogged condition would be highly suitable for *J. curcas*. Based on relationship between drainage and seed yield attained across agro-ecological region, moderate to good yield could be attained under well drained condition (category 3) and moderately well drained/excessively drained condition (category 2) (Fig. 1). Thus suitability criterion for *J. curcas* with regard to drainage was considered as category 3 for high suitability, category 2 for moderate suitability and category 1 (poorly or imperfectly drained condition) for marginal suitability.

Soil depth and performance: It was observed that *J. curcas* was well distributed across diverse soil types with depth varying from less than 20 cm to more than 200 cm (Table 1). Over climates, the locations were distributed under all soil depths with low to moderate and good yields. The medium deep, deep and very deep soils are likely to store and make availability of moisture during dry spells under well distributed rainfall conditions. *J. curcas* with a deep tap root system would provide best defence against drought and would use any residual moisture within the soil profile and survive drought stress. Shallow soil depth will allow only superficial and lateral rooting makes tree more prone to moisture stress. Deep soils would allow trees to find nutrients deeper within the soil. The suitability criteria for *J.curcas* with regard to soil depth was considered as >75 cm for high suitability, 50 to 75 cm for moderate suitability and < 50 cm for marginal suitability (Fig. 2).

Soil texture and performance: Based on relationship of soil texture with yield, low to moderate and moderate to good yields were attained in different locations with soil texture (Fig. 2). The performance of *J. curcas* was poor to moderate in clayey soils, particularly with smectitic clay with poorly drained and anaerobic conditions in rooting zone at various growth stages. Under heavy soils, root formation was significantly reduced. The performance of *J. curcas* in respect of growth and yield was good in loamy, fine soils which have relatively better physical, chemical and fertility conditions compared to other textural classes. The soils predominant with sandy texture in the semi-arid tropics, *J. curcas* was more susceptible to termite attack even leading to mortality in case of severe termite attack. The suitability criteria for *J. curcas* with regard to soil texture was considered as category 4 (loamy) and category 3 (silt loam/clay loam/sandy clay loam/sandy loam) for high suitability, category 2 (loamy sand/clay (mixed) for moderate suitability and category 1 (sandy clay (smectitic) for marginal suitability.

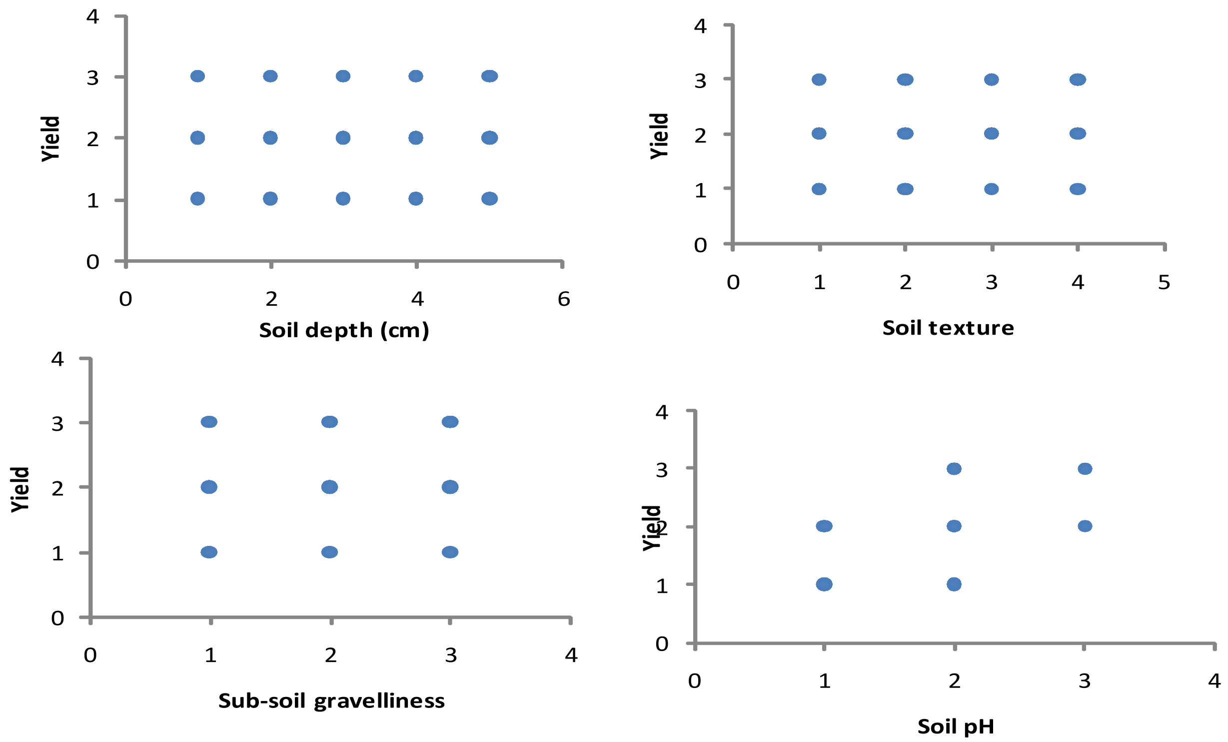

Fig 2. Relationship between soil depth (cm); soil texture; sub-soil gravelliness; soil pH and seed yield of *Jatropha curcus*

Soil pH and performance: The performance (Table 1) either in growth or yield was poor to moderate under moderate to strongly acidic soils (pH < 6) and strongly alkaline soils (pH > 8). Across climates, moderate to good yields of *J. curcas* were attained under pH condition prevailed in category 3 (6.0 to 7.0), category 2 (5.0 to 5.9 and 7.1 to 7.9) as compared to catergory 1 (4.0 to 4.5 and 8.0 to 9.5) (Fig. 2). The suitability criteria for *J.curcas* with regard to soil pH was considered under category 3 (6.0 to 7.0) for highly suitable, category 2 (5.0 to 5.9 and 7.1 to 7.9) for moderately suitable and catergory 1 (4.0 to 4.5 and 8.0 to 9.5) for marginally suitable.

Sub-soil gravelliness and performance: Since *J.curcas* is intended for non-cultivated or marginal lands and with some locations having skeletal soils with gravelliness, sub-soil gravelliness was also considered as one of the soil suitability criteria. The better performance of *J. curcas* was observed under sub-soil gravelliness of < 35% which provided a better tillage and tilth condition and further good anchorage to Jatropha plants/trees and better drainage conditions (Fig. 2). The suitability criteria for *J.curcas* with regard to sub-soil gravelliness was considered as category 3 (< 35%) for high suitability, category 2 (35 to 50%) for moderate suitability and catergory 1 (> 50%) for marginal suitability.

Effect of climate and soil parameters on performance: Using observations on seed yield, climate and soil site parameters, regression models of seed yield were calibrated for predicting yield through different parameters under each climatic zone. The results indicated that coefficient determination (R^2) was high and significant i.e. 0.85 under dry semi-arid, 0.62 under wet-semi arid, 0.72 under dry sub-humid, 0.87 under moist sub- humid, 0.99 under sub- humid, and 0.94 under per humid climatic condition with standard error of 0.38, 0.48, 0.57, 0.48, 0.17 and 0.57 respectively. Under moist sub-humid condition, since numbers of locations were less than number of parameters, two separate models were calibrated. The 1st model was calibrated as a function of rainfall, maximum and minimum temperature and LGP. Therefore, the suitability criterion for *J. curcas* with regard to maximum temperature was considered as 28 to 36 °C for highly suitable, 36 to 42 °C for moderately suitable and more than 42 °C for marginally suitable or unsuitable situations. Mean annual rainfall, minimum temperature, LGP, soil depth and slope were significant under dry semi-arid condition, while flood parameters were significant under moist semi-arid condition. Under sub-humid condition, mean annual minimum temperature, LGP, slope, drainage and flood parameters were significant. There were no significant parameters that would influence seed yield under sub-humid, moist sub-humid and per humid climatic conditions. Based on pooled analysis, R^2 was observed to be 0.45 with standard error of 0.573 for yield prediction. The slope, flooding, sub-soil gravelliness and soil pH were significant for predicting seed yield in different districts. The regression models along with R^2 and standard error under different agro-climatic zones and pooled over agro-climatic zones are given in table 2.

Climate and soil-site suitability criteria: Based on performance of *J.curcas* in its areas of natural distribution and relationship between climate, site and soil parameters and discussed earlier, a range of climate and soil-site suitability criteria were identified for high moderate and marginal suitability condition for growing *J.curcas* (Table 3).

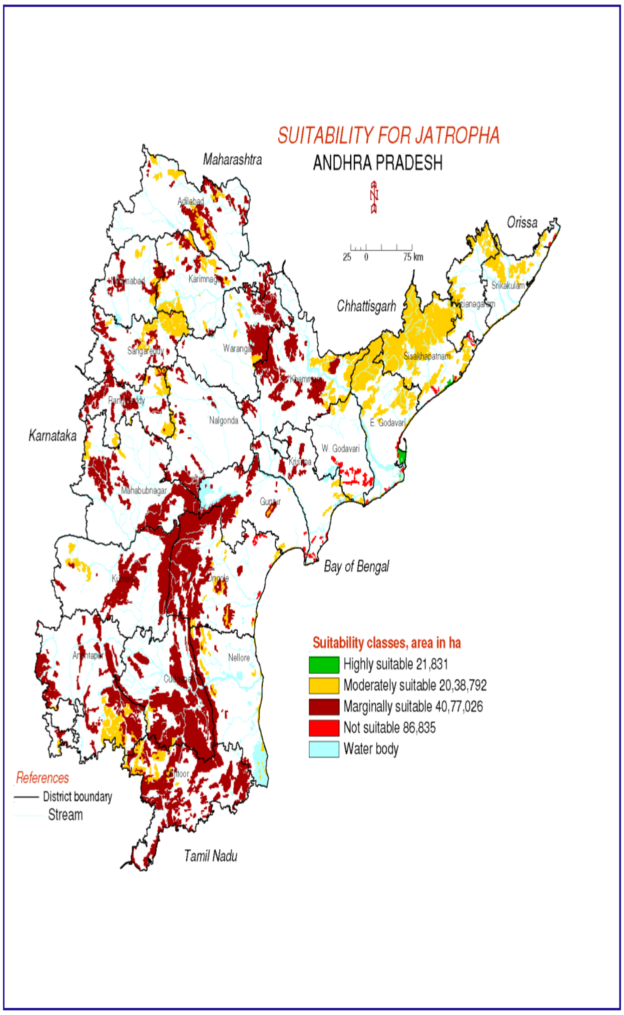

Fig 3. *Jatropha curcas* suitability for non -arable marginal lands of Andhra Pradesh

Table 2. Multiple regression models of *J. curcas* seed yield through climate and soil site parameters

Agro-climatic zones	Number of locations	Multiple regression model	R^2	Standard error
Dry semi-arid zone (500 -750 mm)	23	Y= -8.042** + 0.004* (RF) + 0.044(Tmax)+ 0.130** (T min) - 0.020 (LGP) - 0.158 (Texture) + 0.377 ** (Depth) + 0.693** (Slope) + 0.078 (Drainage) + 0.504 (Flood) + 0.150 (SSG) + 0.757* (pH)	0.854**	0.381
Moist semi-arid zone (750-1000 mm)	24	Y= -2.452 + 0.002 (RF) + 0.002 (Tmax) - 0.005 (T min) + 0.010 (LGP) -0.175 (Texture) - 0.21 (Depth) + 0.225 (Slope) + 0.241 (Drainage) + 0.406* (Flood) + 0.036 (SSG) + 0.160 (pH)	0.624**	0.479
Dry sub-humid zone (1000-1250 mm)	16	Y= 1.176 + 0.001 (RF) -0.075 (Tmax) - 0.038 (T min) + 0.008 (LGP) + 0.075 (Texture) +0.014 (Depth) + 0.682 (Slope) + 0.019 (Drainage) -0.004 (Flood) + 0.088 (SSG) -0.018 (pH)	0.721**	0.573
Moist sub-humid zone (1250-1500 mm)	14	Y= 5.836 + 0.002 (RF) - 0.099 (Tmax) - 0.057 (T min) - 0.020 (LGP) -0.384 (Texture) +0.881 (Depth)	0.870**	0.480
		Y = 0.864+ 0.455 (Slope) +0.182 (Drainage) -0.318 (Flood) + 0.636 (SSG) -0.318 (pH)	0.668	0.627
Humid zone (1500-2000 mm)	14	Y= 4.065*- 0.001 (RF) -0.014 (Tmax) - 0.059* (T min) + 0.008 *(LGP) -0.069 (Texture) +0.291 (Depth) + 0.992* (Slope) -1.382* (Drainage) + 1.496 (Flood)	0.991**	0.169
Per humid zone (>2000 mm)	7	Y= -10.581 + 0.000 (RF) +0.240 (Tmax) - 0.339 (T min) + 0.020 (LGP) -0.431 (Texture) + 0.013 (Depth) + 0.774 (Slope) - 0.058 (Drainage) + 1.316 (Flood) - 1.712 (SSG) +3.566 (pH)	0.937**	0.567
Pooled over locations	99	Y= -1.096 + 0.000 (RF) +0.018 (Tmax) - 0.014 (T min) + 0.002 (LGP) -0.057 (Texture) + 0.31 (Depth) + 0.256** (Slope) + 0.183 (Drainage) + 0.252* (Flood) + 0.249** (SSG) + 0.345* (pH)	0.449**	0.572

RF: Rainfall; Tmax: Maximum temperature; T min: Minimum temperature; LGP: Length of growing period; SSG: Sub-soil gravelliness * and ** indicate significance at $p<0.05$ and $p < 0.01$ levels, respectively

Validation for different locations: The climate and soil-site suitability criteria were assessed for marginal lands in Andhra Pradesh (now Telangana and Andhra Pradesh states). The performance of *J.curcas* in respect of poor, moderate and good was verified with climate and soil-site parameters. Out of total assessed area of 62, 23, 454 ha (100%), about 21, 831 ha (0.35%) is highly suitable; 20, 38, 792 ha (32.76%) is moderately suitable; 40, 76, and 26 ha (65.49%) is marginally suitable (Fig. 3). The suitability groupings were verified with available performance data of *J.curcas* (passport data) which showed a positive relationship with crop performance *i.e.*, highly moderate and marginally suitable lands with performance of *J.curcas* observed as poor, moderate and good crop stand.

Table 3. Climate and soil-site suitability criteria for growing *J. curcas* in different locations

Climatic / Soil-site parameter	Highly suitable	Moderately suitable	Marginally suitable
I. Climate parameters			
Mean annual rainfall (mm)	> 1000	600 - 1000	500 - 600
Mean maximum annual temperature (°C)	28 - 36	36 - 42	> 42
Mean minimum annual temperature (°C)	> 15	6 -15	< 6
Mean temperature during flowering (°C)	< 36	36 - 42	> 42
Length of growing period (LGP) (days)	>180	120- 180	90 - 120
Proneness to frost (days)	No frost conditions	No frost conditions	1- 2
II. Site parameters			
Altitude (m above msl)	< 500	500 -1000	> 1000
Slope (%)	< 5 (Flat lands/nearly level / very gently sloping)	5 -15 (Gently sloping/ undulating land)	> 15 (Rolling lands/ steeply or moderately steeply sloping lands/hills and ridges etc.)
Drainage	Well drained No flooding	Moderately well drained / Excessively drained	Poorly/Imperfectly drained
Proneness to flooding/water logging (days)		Slight flooding (< 3 days)	Moderate flooding (< 6 days)
III. Soil parameters			
Soil depth (cm)	> 75	50 - 75	50
Texture	Loamy, Silty loam, clay loam, Sandy clay loam, Sandy loam	Clay (Mixed / Kaolinitic), Loamy sand	Clay (Smectitic), Sandy
Sub soil gravelliness (%)	< 35	35 - 50	> 50
pH (soil reaction)	6.0 to 7.0	5.0 - 5.9 and 7.1 to 7.9	4.0 - 4.5 and 8.0 - 9.5

Conclusion

The climate and soil-site criteria for *J.curcas* can be used for assessing available uncultivated lands which may be marginal, degraded or any potential lands (otherwise not intended for cultivation). The suitability maps developed on the basis of these which can be a useful tool in the selection of potential areas for *J.curcas* in a macro-climate level.

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