



Jatropha curcas: a potential biodiesel crop and its current R&D status

S K DHYANI¹, R V KUMAR² and S P AHLAWAT³

National Research Centre for Agroforestry, Jhansi, Uttar Pradesh 284 003

Received: 1 June 2010 ; Revised accepted: 28 January 2011

ABSTRACT

The need of alternatives of fossil fuel is pressing hard for several reasons, especially to the countries like India with vibrant economy which consumes large amount of fossil fuels and rely heavily on import for the same. Among several oil-yielding crops and tree-borne oilseeds, *Jatropha* has been identified as most potential plant for biodiesel due to its advantages over other plant species. Concerted R&D works on bio-fuel species like *Jatropha* started in 2003 after the committee constituted for bio-fuel development in India presented its report to Planning Commission and then several organizations like ICAR, NOVOD Board, DBT, DST, DRDO, and CSIR started funding on R&D of TBOs to several research institutions including SAUs. Immediately, first national programme on *Jatropha* cultivation was initiated in 2004, with a target of 4 lakh ha plantation, which could not be achieved in absence of suitable varieties and improved planting materials. At present the R&D efforts were focused on collection, evaluation and conservation of its germplasm, understanding its breeding behaviour, standardization of nursery and propagation techniques, development of cultivation packages for different soil and climatic conditions, machines for bio-diesel production etc. A large number of accessions from almost all the areas of its distribution in the country have been collected by research institutions. Good amount of variability has been recorded in morphological traits, seed yield and oil content. Genotypes having high seed yield and oil content have been selected from germplasm evaluation trials but their consistency over the years and environments yet to be confirmed. Seed yield has been improved to a limited extent through intraspecific hybridization but breakthrough will only be possible by the development of inbred lines and intensive breeding programmes, which will take long time. The agro-techniques for raising plantation has been standardized up to limited extent as fertilizer and irrigation requirements are yet to be worked out for different types of soil and climatic conditions. Though, propagation techniques through seed, cuttings and tissue culture are well developed. Chemical composition of oil, cake and biodiesel, its suitability for engines have already been assessed but there is need of intensive work on value-addition like detoxification of cake to make it suitable for cattle feed. As *Jatropha* cultivation is projected for the wastelands, the development of varieties for moisture stress, degraded and marginal lands are urgently required. In nutshell, *Jatropha* research is still at the beginning with respect to genetic improvement for increasing seed and oil yield. High variability provides good opportunity for selection of desired types and success in breeding programme. The article summarizes the need of the hour, current status of R&D efforts and future strategies to be made.

Key words: Biodiesel, *Jatropha curcas*, Oil content, Plantation, Propagation, Yield

Ever-increasing human population and rapid pace of development is resulting in high demand of petro-products. Considering the increasing cost of petroleum products, depleting their reserves and the pollution caused by the use of fossil fuels, many developed countries, particularly USA, Germany and Australia have ventured into the use of vegetable oils as a viable alternative of diesel. Several western countries have invested huge sums in research and development to promote the use of bio-diesel on a commercial scale.

¹Director (e mail: shivkdhyani@gmail.com), ²Principal Scientist (e mail: rvkumar4@rediffmail.com), ³Senior Scientist (Plant Breeding) (e mail: ahlawatp@gmail.com)

In India, selected non-edible oils obtained from seeds of tree species are being used for bio-diesel purpose, some of which have been traditionally used in the rural areas for lighting purpose. Important tree-born oilseeds species (TBOs) used in India are neem (*Azadirachta indica*), karanj (*Pongamia pinnata*), mahua (*Madhuca* spp), undi (*Calophyllum inophyllum*) and *Jatropha* (*Jatropha curcas*). While the first four species grow into big tree, *Jatropha* is shrub to middle sized tree that starts bearing fruits from the second year onwards. For India, bio-fuel projected to be the most promising with *Jatropha* considering all other factors. Apart from using as oilseeds, *Jatropha* has medicinal value and is being used traditionally for curing various ailments in

India. It is estimated that the existing potential of tree-borne oilseeds in the country is 3–3.5 million tonnes but only 0.5–0.69 million tonnes are being collected. In spite of the efforts made by the various states the actual area brought under *Jatropha* cultivation is only 3 lakh ha, which is not at all satisfactory as compared to the massive demand (IARI, 2007). In the present paper an attempt has been made to review the current R&D status of *Jatropha* in the country and suggest future strategy for its improvement.

Energy scenario of India

The energy scenario of India is characterized by a mix of non-commercial and commercial sources of energy, viz cow dung, agriculture waste, fuelwood, coal, hydro, oil, gas, wind and solar etc. The share of oil in this energy scenario is about 30% of total energy consumption of India, of which 74 million tonnes of crude oil (70% of its requirement) were imported in the early years of 21st century causing heavy burden of foreign exchange. Crude oil price has been fluctuating violently in the international trade as has often led to war like situations. The indigenous oil availability in India has increased from 0.25 million tonnes in 1947 to about 33.30 million tonnes in 2004–05 (Kureel, 2007). But due to rapid economic surge, the increasing demand is constantly outstripping the increase in indigenous availability and production of crude oil. India would need approximately 150 million tonnes of crude oil by the current year as against the optimistic estimates of indigenous production of crude meeting the high demand of oil to meet the growing energy needs, but also to check ill effects of oil imports, which make the economic growth vulnerable to uncertain world oil supply and price situation.

With insufficient oil resources, India cannot rely on imported oil, which has seriously affected its economic development. Therefore, as a matter of necessity and national self-reliance, India has to strive to achieve self-sufficiency in fuel availability. India rank fifth in the world after the US, China, Russia and Japan in terms of fossil fuel consumption. World energy consumption and per cent contribution by different sources are presented in Table 1. The Table indicates that after coal, crude oil is the major contributor of the energy in India, however, there is a huge gap between annual requirement and domestic production of petroleum products. The huge gap between demand and supply is only met through import. India imported crude petroleum around 147 million tonnes during 2007. The increasing trend of import burden is not a healthy sign and if the corrective measures are not taken in time, a large part of money will drain out in the import of petroleum products.

In the backdrop of rapid depletion of the fossil fuel reserves, high prices and associated environmental degradation, biofuels are gaining importance. Biofuels not only fulfill traditional domestic needs such as cooking, heating or lighting but also cater to new energy applications

Table 1 World energy consumption (million tonnes)

Country	Oil	Gas	Coal	Nuclear	Hydro	Total
USA	943.1	595.7	573.7	192.1	56.8	2 361.4
China	368.0	60.6	1 311.4	14.2	109.3	1 863.5
UK	78.2	82.3	39.2	14.1	2.1	215.9
Canada	102.3	84.6	30.4	21.1	83.3	321.7
India	128.5	36.2	208.0	4.0	27.7	404.4
India (%)	32	9	51	1	7	100
World	3 952.8	2 637.7	3 177.5	622	709.2	11 099.2

Source: BP Statistical Review of Energy 2008

at a cost competitive with equivalent fossil-based technologies. That is why researchers all over the world are looking for alternative fuels on sustainable basis. Biofuels are renewable source of energy derived from biological raw material. Biofuels – ethanol and biodiesel are gaining worldwide acceptance as one of the solutions for problems of environmental degradation, energy security, restricting imports, rural employment and agricultural economy. Government of India launched “National Mission on Biodiesel” to find a cheap and renewable liquid fuel-based on vegetable oils (Shukla 2005). However, shortage of raw material to produce biodiesel is a major constraint (Wani *et al.* 2006). In this scenario, biofuels, particularly *Jatropha* derived from renewable source hold immense potential for meeting India’s future energy needs.

Jatropha

The country has enormous potential of oilseeds of tree origin like oilpalm, mahua, neem, simarouba, karanja, ratanjyot, jojoba, cheura, kokum, wild apricot, bhikal, wild walnut, kusum, tung etc. which can be grown and established in the wasteland of varied agro-climatic conditions. These have domestic and industrial uses like agriculture, cosmetic, pharmaceutical, diesel substitute, cocoa-butter substitute etc. Most of these TBOs species are scattered in forest and non-forest areas and hardly 20% of the existing potential is being crushed and utilized that too of poor quality due to lack of awareness of their uses, poor collection and marketing system. Among the various tree-borne non-edible oilseeds, *Jatropha curcas* is getting priority over others due to several advantages. These include, firstly, being a shrub it is easy to manage, harvest seeds and has shorter gestation period than other species. Secondly, being hardy, it is easy to establish and grows quickly. Thirdly, genus has a large number of species (approximately 170) distributed in varied agro-climatic conditions with six native species (Rathakrishnan and Paramathma 2009), hence, can provide good material for improvement programme. Fourthly, the seed collection period of *Jatropha* does not coincide with monsoon when most of the agricultural and plantation activities are undertaken. This provides an opportunity for additional employment generation. Fifthly, it is not eaten away by the cattle. Sixthly,

it is less affected by major diseases or pests, except in few pockets, however, monoculture of the species may face unexpected pests and disease infestations (Shanker and Dhyani 2006). Seventhly, the byproducts of biodiesel are also quite useful for industrial application such as glycerine and biofertilizers. The residue is a good substrate for biogas production. Finally, because of its drought endurance and adoption to wide agro-climatic conditions it can be planted on less fertile lands where ultimately it may help in soil conservation and improvement of soil quality.

It is highly probable that centre of origin of the *Jatropha curcas* is in Mexico and central America. It is found in wild and cultivated forms throughout Africa and Asia. In India, Portuguese navigators introduce this species in 16th century and now it occurs almost in all tropical parts of India. It is well adapted to semi-arid conditions and can withstand long drought periods. The tribal people have patronized *Jatropha* in western belt of Madhya Pradesh, eastern districts of Gujarat, Chattisgarh and south-eastern parts of Rajasthan. It is also found in parts of Uttar Pradesh, Uttrakhand, Maharashtra, Andhra Pradesh, Karnataka, Jharkhand and Tamilnadu.

Since, *Jatropha* plantations is focused largely on unproductive lands that are located in poverty-stricken areas and in degraded forests, its growth and productivity will be affected by various abiotic stresses. Therefore, an understanding of genetic basis of drought endurance/resistance in *Jatropha* is a pre-requisite for a geneticist to evolve superior genotype through either conventional breeding methodology or biotechnological approach. This has been discussed in detail in the following pages.

National biofuel programme of India

The committee constituted for biofuel development in India presented its report to Planning Commission in 2003. The report recommended multi-dimensional programme for biodiesel development in the country to ensure 20% contribution of biodiesel of the total diesel demand. The potential demand of diesel and estimated requirement of biodiesel at different blending levels and area required for the same is presented in Table 2.

National Policy on Biofuels and for its implementation a

National Biofuel Coordination Committee under the chairmanship of the Prime Minister was established in December 2009 to provide policy guidance and coordination. The Ministry of New and Renewable Energy (MNRE) has been designated as the coordinating Ministry for biofuel development and utilization, while specific roles have been assigned to other ministries concerned. The salient features of the National Policy on Biofuel include biodiesel production from non-edible oil seeds in waste/degraded/ marginal lands; target of 20% blending by 2017 proposed; minimum support price (MSP) for non-edible oil seeds and minimum purchase price (MPP) for purchase will be announced with periodic revision; and granting of financial incentives, including subsidies and grants.

First National programme on *Jatropha* cultivation released during March 2004, with an outlay of ₹ 800 crores was primarily meant for raising *Jatropha* nurseries and plantations in 2 lakh ha lands. The whole programme had outlay of ₹1 500 crores for *Jatropha* plantation on 4 lakh ha in next five years. The goal of this ambitious programme was to produce 2.6 million tonnes of biodiesel from *Jatropha*. It was expected that once the 4 lakh ha area comes under *Jatropha* plantation, it will yield 0.5 million tonnes biodiesel and tremendous quantity of cake for fertilizers. This will provide opportunity for 16 million man-days/year of work for rural folk.

Climate and soil

Jatropha is found in the tropics and subtropics. Though, it likes hot climate but can withstand low temperature and light frost. It can be very well grown in a wide range of agroclimatic conditions including moderate to high temperature areas (up to 45°C). Very cold areas (<10°C) do not suit *Jatropha* and retard its growth. . It grows in different kinds of soil almost anywhere even on gravelly, sandy and saline soils It can thrive on the poorest stony soil (De Chelmicki and De Varnhagen 1841, De Avila 1949, Levingston and Zamora 1983, Martin and Mayeux 1984). The leaves shed during the winter form mulch around the base of the plant. The organic matter from leaf litter enhances earthworm activity in the soil around the root zone of the plants, which improves the fertility of the soil. Its water

Table 2 Potential demand of diesel and estimated requirement of biodiesel at different blending rates and related area coverage

Year	Diesel demand (million tonnes)	Biodiesel (million tonnes) requirement for blending and related area coverage (million ha)					
		Biodiesel @5%	Area for 5%	Biodiesel @ 10%	Area for 10%	Biodiesel @ 20%	Area for 20%
2005-06	49.56	2.48	2.07	4.96	4.14	9.91	8.28
2006-07	52.33	2.62	2.19	5.23	4.38	10.47	8.76
2011-12	66.90	3.35	2.79	6.69	5.58	13.38	11.19
2016-17	83.58	4.18	3.48	8.36	6.97	16.72	13.98

Source: Mandal 2005, Planning Commission 2003

requirement is extremely low and it can withstand long period of drought by shedding most of its leaves to reduce transpiration loss. It can be very well cultivated where annual rainfall is between 300 and 1 000 mm and average annual temperature is above 20°C but can grow at higher altitudes and tolerates slight frost as well.

Propagation

Seeds are the most easy and reliable material for its propagation. Optimum time for raising its nursery is February to mid of March. For raising the nursery of *J. curcas*, seeds are sown in 30 cm pots containing clay, sandy or calcareous soil or a mixture of equal proportions (by volume) of two or all three soil types (all possible combinations) in different compositions of the three component soil types. The clay + sand mixture gave the highest percentage germination (>80%) and the second fastest germination rate (the fastest was obtained with the sandy soil). Clay + sand resulted in the greatest seedling height, stem diameter and number of branches but clay soil resulted in the highest number of leaves and total leaf area (Laila and Zarad 1994). Another simplest method of propagation of *Jatropha* is direct seeding, wherein two seeds are placed in pits (45 cm³) at the onset of rainy season or after first good rainfall.

Vegetative propagation (conventional methods)

It can be easily propagated through stem cuttings and air layering. Stem cuttings of 25 cm length from more than one year old branch are taken during February, treated with low concentration (150–400 ppm) of IBA for overnight and planted in polybags or sand beds for rooting. Fair rooting and survival can be obtained through this method. Thick cuttings of 1.8–2.5 cm diameter gives better rooting than thin 1.0 cm diameter cuttings. Rooting takes place in 30–45 days. Cuttings become ready for transplantation by the planting season in July. Several other research workers have tried to study the effect of growth regulators on root formation in *Jatropha* by using cuttings and other explants of this species. The cuttings (25–30 cm long and 2–3 cm diameter) taken from middle portion of one year old branches, treated with 600–800/mgl thiamine and 100–400/mgl IBA, IAA and NAA gave 100% rooting during spring season. The rooting rate of cuttings and air-layers with thiamine treatment was high during monsoon season and poor in case of growth hormones. The cleft grafting has been reported more successful than other methods during spring season (Dhillon *et al.* 2009a). The effect of IBA on root formation of stem cuttings of *J. curcas* was studied by using four levels of IBA (hormone) concentration, ie 0, 2 000, 4 000 and 6 000 ppm and three kinds of rooting media, ie coarse sand, rice husk charcoal and coarse sand mixed with rice husk charcoal in the ratio 1:1 (Narain and Watna 1983). Rooting in the stem cuttings with the untreated (hormone) treatments were noticeably better than the treated ones. Root formation in

sand was prominently better than in coarse sand mixed with rice husk charcoal and rice husk charcoal only. So keeping this in mind, an experiment was conducted at National Research Centre for Agroforestry, Jhansi, to standardize the concentrations of growth hormones in which different concentrations of IBA, ie 0, 25, 50, 75, 100, 125 and 150 ppm (24 hr treatment) and 0, 500, 1 000, 1 500, 2 000 and 2 500 ppm (3–4 minutes treatment) were tried for vegetative propagation through stem cuttings of *J. gossypifolia*. Results indicated that IBA concentrations of 50 and 75 ppm (24 hr dip) and 1 000 and 1 500 ppm (3–4 minute dip) were reasonably superior to other treatments in relation to rooting response, survival and growth of rooted plants (Kumar and Swarnkar 2003).

Propagation through tissue culture

Jatropha has been successfully propagated through tissue culture (Sujatha and Dhingra 1993, Sujatha and Mukta 1996, Jyoti *et al.* 1998, 2000, Rajore *et al.* 2002). Prolific adventitious shoot bud initiation has obtained using a combination of 2.2 or 4.4 µM BA and 4.9 µM IBA. Reduction of IBA concentration (2.5 µM) promoted further development of shoots. Regenerated shoots rooted readily on MS medium lacking growth regulators. Plantlets were acclimatized and successfully transferred to pots (Sujatha and Dhingra 1993). Simultaneously, regeneration from hypocotyl, petiole and leaf explants of *Jatropha* has been evaluated on a range of concentrations of zeatin, kinetin and N6-benzyladenine (BA) either singly or in combination with IBA. Higher regeneration from hypocotyl and petiole explants was obtained on BA with IBA than on zeatin- or kinetin-supplemented media. Leaf discs from the third expanding leaf exhibited higher regeneration potential than those from the fourth leaf. Independent of the explant type, direct adventitious shoot bud induction was recorded highest on MS medium supplemented with 2.22 µM BA and 4.9 µM IBA. Although the same BA concentration but with reduced IBA concentration (0.49 µM) proved effective in callus mediated regeneration from hypocotyl and leaf explants. Regenerated shoots could be rooted on growth regulator-free gelled full-strength MS medium. Following simple hardening procedures, the *in vitro*-raised plants could be transferred to soil and grown to maturity in the field (Sujatha and Mukta 1996). Similarly, regeneration has been possible from shoot-tips of *J. curcas* on a combination of GA₃ (3.0 mg/litre) and IAA (3.0 mg/litre) on MS medium. Plantlets were acclimatized and successfully transferred to pots and finally to the field (Jyoti *et al.* 1998).

An efficient two-stage method for plant regeneration from leaf explant-derived embryogenic callus of *J. curcas* has also been developed and standardized (Jyoti *et al.* 2000). Embryogenic callus and formation of globular embryos were induced on MS-Gamborg's medium containing MS basal salts and Gamborg's vitamins, supplemented with BA (3 mg/

litre) + IAA (3 mg/litre). Subsequently, plantlets were induced on MS medium + gibberellic acid (3 mg/litre) + IAA (1 mg/litre). Influence of different culture media, hormonal regimes, light and sucrose on somatic embryogenesis was also investigated. Upon transfer to soil, the plantlets grew well and appeared normal; there was no mortality of plantlets. *In vitro* production of multiple shoots from nodal segments has been developed on MS medium fortified with 2.0 mg/litre Kn and 1.5 mg/litre IBA. However, addition of some additives, viz ascorbic acid (10.0 mg/litre) + citric acid (50.0 mg/litre) + adenine sulfate (25.0 mg/litre) + glutamine (100.0 mg/litre) showed a synergistic effect on shoot proliferation and their development. Best rooting was achieved on 1/2 strength MS medium with NAA (5.0 mg/litre). The plantlets were acclimatized by transferring in a sterilized mixture of soil and vermiculite (3:1) and were established in soil with a survival rate of 70±10% (Rajore *et al.* 2002).

Plantation

Jatropha plantations can be raised in numerous patterns depending on the conditions of field and types of land. The package of practices for block plantation, bund plantation and mix cropping are being worked out. Any one of the said plantation technique may be adopted given the agro-climatic conditions of the region and/ or micro farming situations.

Block plantations of different spacing like 2×2 m, 3×2 m, 3×3m etc. depending on the quality of soil and input management can be done for its cultivation. The plant intensity will vary accordingly. Pits of 45×45×45 cm are dug, filled with topsoil and farmyard manure before the transplantation is carried out. Fertilizer mixture of N, P, K at 15:15:15, applied @ 250 g/plant at the onset of the rainy season, gives good results. Another most preferred method is bund plantation which is very common in Madhya Pradesh, parts of Rajasthan and Gujarat. In this method, the plants are planted along field bunds at spacing of 1 m. Bund plantations usually forms as a vegetative fencing in several parts of central India, and Jatropha is among the prime choice.

Agroforestry

In agroforestry system, *J. curcas* has been intercropped with annual crops such as cowpea, sesame, sunflower, French bean, blackgram, greengram and groundnut etc. at various places (Dhyani *et al.* 2009). Good yield of wheat (var. Lok 1) intercrop 3.04 tonnes/ha has been obtained at NRCAF, Jhansi up to third year under Jatropha plantation spaced at 3 m × 3 m. Reduction in wheat yield was non-significant over the sole crop and attributed to the space occupied by the Jatropha plants. Jatropha is also planted at spacing of 4 m × 4 m or more giving enough space for inter-cropping with crop like *Piper longum*, *Curcuma longa*, *Zinziver officinale*, *Asparagus racemosus* and *Comiphora weightii*. In the ravine areas Jatropha can be intercropped with the plants like *Asparagus racemosus* and *Piper longum* at 2 m ×

2 m spacing for conservation of support species and reclamation of ravine areas. It can be intercropped with *Comiphora weightii* at a spacing of 5 m × 5 m. Mixed cropping model and strategies for large-scale cultivation of *J. curcas* under agroforestry have been suggested by Bhattacharya and and Joshi (2006).

J. curcas can also be included in agroforestry programmes to ameliorate the environmental, social and economic status of the countryside. Chemical fertilizers adversely affecting the chemical balance of the soil can be replaced by *J. curcas* cake as organic fertilizer (Chaudhari and Joshi 1999). The promotion of the use of Jatropha oil could also provide a poverty alleviation option in the rural areas. Farmers can use vacant, waste and marginally used land for growing such trees and benefit from the annual produce, which will add as their income. With the increased green cover the environment will also benefit greatly (Ram Newaj and Dhyani 2008).

Agronomy package

Agronomical practices for different soils, agro-climatic conditions and type of plantations are being advocated. Effect of different plant densities (3333 and 2500 plants/ha) and fertilizer levels on growth of Jatropha were studied on slopy lateritic soils. The different spacings (2 m×1.5 m and 2m×2 m) did not affect growth. However, with increase in levels of fertilizer the plant height, girth, leaves/plant, petiole length, leaf area/plant, leaf area index (LAI) and absolute growth rate (AGR) of height and girth increased, progressively. Application of 3.6 g each of N and P₂O₅, and 2.0g K₂O/plant at the wider spacing produced maximum height (67.2 cm), girth (7.5 cm) and AGR of height (7.30 cm/month), whereas the LAI and leaves/plant was maximum at closer spacing. The interaction effects between spacings and fertilizers were non-significant (Jadhav *et al.* 1995).

Fruiting

Fruiting starts in September and continues up to January. Period of fruit development and maturity ranges from 55 to 61 days from the date of first fruit initiation (Dhillon *et al.* 2006). The biochemical changes in seeds and pods during the development of *J. curcas* were studied at Bawal, Haryana. The fresh and dry weights as well as the size (length and diameter) of pods and seeds increased during development (17–57 DAA-days after anthesis). The pods remained green up to 47 DAA then turned yellow at 57 DAA. Seeds were white at 17–27 DAA, brown at 37–47 DAA, and black at 57 DAA. The water content of seeds and pods decreased from 26 to 67 DAA. The per cent germination increased from 17 to 57 DAA. The highest per cent germination (85%) was observed at 67 DAA (Kaushik *et al.* 2001). Harvesting often takes place during the end of rainy season. The fruits are manually plucked from branches. Manual harvesting is adequate and can be a good source of income for women workers.

Seed and oil yield

Seed and oil yield reported so far in the literature vary considerably. The range of seed oil and seed yields can be attributed to a variety of factors such as climate, intensity of management, site quality, size of plant and genetics. The seed yield of *J. curcas*, *J. gossypifolia* and *J. podagrica* are 5.0 tonnes, 0.5 tonne and 0.4 tonne/ha annually and seed shell to kernel ratio are 44:56, 35:65 and 25:75, respectively. The kernel oil contents are 47–52%, 29% and 54%, respectively (Raina and Gaikwad 1987). The seed oil content of 85 accessions of Rajasthan, Uttarakhand, Uttar Pradesh and Madhya Pradesh varied from minimum of 22.8% to 40.3% (Kumar *et al.* 2008). However, in general the latest data on seed yield does not support earlier estimates, especially on plantation basis. It may be possible from individual plant. The high seed yield should be expected only from elite plants under the most favourable growing conditions. *J. curcas* seed contain around 40% of a semi drying oil at 7% moisture. The oil is extractable by solvent extraction or mechanically by using the hydraulic press or a simple screw press (Chaudhary and Joshi 1999; Patil *et al.* 2003). Its fresh oil is almost colourless and odourless, and on standing acquires a pale yellow colour.

Pollination ecology

J. curcas is monoecious and protandrous. Both flower sexes open synchronously. The sexual system facilitates geitonogamy (self-pollination) and xenogamy (cross-pollination). The flower visitors include bees, ants, thrips and flies. Bees and flies affect geitonogamy and xenogamy while ants and thrips affect only geitonogamy. Being predominantly cross-pollinating, the plant throws open the possibilities for geitonogamy. In line with this, the plant might be selectively eliminating the growing offspring, especially those originated from geitonogamy, in order to allocate resources for the xenogamous (Raju and Ezradanam 2002). In such a system of pollination behaviour, maintenance of genetic purity of planting material obtained through seeds will be a challenge. Hence, propagation of elite plants through asexual methods is the only option (Raju and Ezradanam 2002).

J. curcas have 10 stamens, each of which bears four microsporangia. The development of the anther wall is of dicotyledonous type, and is composed of an epidermis, endothecium, middle layer(s) and glandular tapetum (Liu *et al.* 2007). The life-span of the male flower is about two days and pollen viability is relatively high, i.e. 9 hr after blooming and becomes low 33 hr later and pollen hardly has any viability after 48 hr. The life-span of the female flower is about 5–12 days. The stigma receptivity is strong during 1st–4th day and begins to decline 5th day onwards and completely loses its receptivity on 9th day. There is no obvious secretion on the stigma. The higher proportion of green stigma indicates stronger receptivity. As *J. curcas* shows protandry, the female

flowers open later, with 60% opening from the 3rd to 5th day. In a few racemes the female flowers opened first shows a tendency to promote xenogamy and minimize geitonogamy (Chang-wei *et al.* 2007).

In India, flowering was observed at the terminal end of branches after rainy season. However, some plants flower even in spring season (March–April). The average male to female (M/F) flower ratio was 20:1, which changes drastically (108:1) with the fall in temperature. Usual peak period of flowering varies from 3 to 20 days (Dhillon *et al.* 2006). Variation in the M/F ratio per inflorescence was recorded during the first year with average M/F ratio of 25:1, and it reduced to 13:1 in the second year indicating a positive trend towards productivity (Prakash *et al.* 2007). Female flower/inflorescence had high variation; while the difference for number of male flowers/inflorescence was narrow (Kumar *et al.* 2008). Alam *et al.* (2009) studied augmenting pistillate flowers with exogenous application of growth regulators and chemicals in *J. curcas* and found positive effect on increasing inflorescence but suggested further critical observations. Similarly, increase in number of female flowers and fruit yield due to exogenous application of GA (10 and 100 ppm) reported by Makwana *et al.* (2010). Forenoon pattern of anthesis with subsequent pollen release indicated with each male flower producing 1617 ± 100 pollen with pollen:ovule ratio as 539:1. The stigmas become receptive 2 hr after anthesis, coinciding with nectar secretion and pollen presentation schedule. Each female flower (4.54 ± 0.82 IL) produces higher amount of nectar than male flower (1.92 ± 0.44 IL) (Bhattacharya *et al.* 2005). Among 17 species of floral visitors, 11 species were reported pollinators (*Apis dorsata*, *A. florea*, *A. mellifera*, *Eumenes conica* and *Vespa* sp.) with two floral visiting peaks at 10.00–12.00 and 16.00–17.00 hr everyday (Qing *et al.* 2007). Among the different insect visitors *Apis* spp were the most frequent. Sucrose level influence flower-visit duration, pollen removal and deposition on stigmas by honeybees (Bhattacharya *et al.* 2005).

Inter- and Intra-specific hybrids

The genus *Jatropha* is a morphologically diverse genus comprising 160–175 species of shrubs, rhizomatous subshrubs and herbs. In addition to their use as ornamental, medicinal and energy crops. *Jatropha tanjorensis*, a species found abundantly in the Tanjore, Pudukottai, Trichirapalli and Ramnad districts of Tamilnadu and grown as a fence plant, showed intermediacy in phenotypic characters of *J. curcas* and *J. gossypifolia*. Cytological and peroxidase isoenzyme studies revealed that *J. tanjorensis* is a natural inter-specific hybrid between these two species. Since there was no seed set, propagation through tissue culture using leaf discs was attempted (Prabakaran and Sujatha, 1999). Inter- and intra-specific hybridization between 15 potential *J. curcas* clones using as female parent and related wild

species, viz *J. integerrima*, *J. podagrica*, *J. villosa*, *J. tanjorensis*, *J. gossypifolia*, *J. glandulifera*, *J. multifida* and *J. maheshwarii*, using as pollen donors were attempted (Partibhan *et al.* 2009). Varying degree of success in crossing programme was observed. *J. curcas* and *J. integerrima* produced successful hybrids with more seed set, while other crosses failed to produce seed due to crossability barriers. The F₁ had vigorous growth but fruits size was small, indicating dominance of *J. integerrima* traits. It is being improved through back cross programme. At NRCAF, Jhansi, the intraspecific reciprocal crossing between selected 10 parents of *J. curcas* has resulted in significant increase in fruit yield and ratio of female to male flowers/inflorescence (1:8) of the F₁ hybrids.

Mutation

Mutation is a potential technique for inducing variation in *Jatropha*. Dry seeds of *J. curcas* were gamma-irradiated with 6, 12, 18 and 24 kR and grown in soils of different alkalinity. Several leaf abnormalities resulting from irradiation and a dose dependent decrease in mean growth rate were reported. A similar response was noted in control and treated plants to alkaline soils (Pandey *et al.* 1998). In another study on the effects of various doses of gamma ray on cotyledons, seedlings with three rather than the normal two cotyledons were observed at frequencies of 5.9, 7.5, 10.9 and 5.0% following the 0, 6, 12 and 18 kr treatments. Changes in cotyledon position, shape and size and stomata number were also observed following irradiation. The results indicate that mutagenesis has the potential of inducing desirable variation in *J. curcas* (Pandey and Datta 1995).

Enzymatic activity

Analysis of the enzymatic activity of laccase, cellulose, peroxidase and polyphenol oxidase revealed that these enzymes are expressed differentially during the growth and development of the plant. Further, their activity varied among the genotypes from the analysis of 50 accessions (Kumar *et al.* 2007). Two new esterases (JEA and JEB) and a lipase (JL) were reported from the seeds of *J. curcas*. Lipase activity was only found during germination of the seeds and increased to a maximum after four days of germination. All enzymes were found to be most active in the alkaline range at around pH 8 and the purified esterases were very stable at high temperature. Most ions caused a negative influence on the activity of both esterases (Staubmann *et al.* 1999).

Genetic diversity in *Jatropha*

The DNA from 34 accessions of eight *Jatropha* species, viz *J. curcas*, *J. gossypifolia*, *J. glandulifera*, *J. integerrima*, *J. podagrica*, *J. multifida*, *J. villosa* vs *J. ramnadensis*, *J. maheshwarii*, and natural hybrid *J. tanjorensis* were subjected to molecular analysis using 250 RAPD, 50 ISSR and 50 organelle specific microsatellite primers from other

angiosperms. The nuclear marker studies revealed high inter-specific genetic variation (98.5% polymorphism) corroborating with the morphological differentiation among the eight species (Basha and Sujata, 2009). In another study, the parents and 23 inter-specific hybrids (reciprocal) between *Jatropha curcas* and *J. integerrima* were subjected to RAPD analysis of 61 primers. The similarity value between the parents (41.4%) was less than those between parents and hybrids. Cluster analysis based on Jaccard's similarity coefficients outgrouped the female parent from rest of the genotypes at a similarity coefficient of 0.55 (Dhillon *et al.* 2009b). Genetic diversity and interrelationship among 26 germplasm of *J. curcas* has been assessed through RAPD analyses. Out of 55 decamer primers, 26 primers produced a total of 6011 amplified products and from which only 1 859 bands (30.92%) were polymorphic and varied from 300–2 500bp. UPGMA using average cluster analysis revealed clear genetic differences among the germplasm (Kumar *et al.* 2009). The genetic divergence analysis revealed marked differences among the 10 accessions of species for morphological traits, ie plant height, collar diameter, number of branches and branch length (Kumar *et al.* 2005). An analysis of intra-specific variation and interrelationships between morphology, nutritional content and enzymatic activity of 27 accessions of *J. curcas* has revealed significant differences among the accessions for branch length, crude protein, ADF, NDF, cellulose, hemicellulase, lignin, peroxidase and polyphenol oxidase. Principal component analysis showed 58% of total variation in the measured traits and negative correlation between four morphological traits and nutritional compounds. A strong correlation is reported between plant height, branch length, number of branches and collar diameter (Kumar *et al.* 2008).

DNA fingerprint methods for estimation of genetic diversity and relatedness in *J. curcas* plant populations appear extremely promising, particularly for analysis of eco-geographical variation, breeding and conservation of genetic resources. This information will enable the breeder to take decision regarding selection of diverse parents to be used in crossing in order to maximize the expression of heterosis.

Marker-assisted selection

The first requirement in marker-assisted selection of a trait of interest, be it monogenic or polygenic, is gene mapping through DNA markers. The utility of DNA markers in *J. curcas* breeding is based on finding tight linkages between the markers and genes of interest. Such linkage permits one to infer the presence of a desirable gene by assaying for the marker. Breeders of *J. curcas* can frequently transfer disease resistance traits from one genetic background to another. Of particular potential value to the *J. curcas* breeder is DNA marker diagnostic of traits, which are difficult to measure. An excellent example of such trait is nematode resistance, which requires one to dig up the plant and examine

the roots. Nematode resistance was one of the first traits associated with molecular in any plant (Paterson 1996).

The introduction of DNA marker-aided selection will overcome major limitation of backcross breeding in *J. curcas*. If the genes to be transferred are marked by tightly linked DNA markers, segregating populations of plants can be screened at the seedling stage, before the trait is expressed, for the presence of the gene(s) of interest. Since the DNA markers can be used to mark quantitative trait loci (QTL) as well as major genes, there are no limitations to the types of characters that can be manipulated by marker-based selection. Without linked markers it would be extremely difficult and time consuming to monitor the flow of such genes in a breeding programme of *J. curcas*. DNA marker-aided backcrossing has been very widely used by commercial firms, savings of even 1–2 generations means that improved cultivars reaches the market place sooner. Further, by using DNA markers to identify recombinants, introgressed chromosome segments might be trimmed to minimal size, reducing the extent to which the recurrent genotypes is disrupted by undesirable alleles closely linked to the target trait (Paterson 1996, Tanksley and McCouch 1997, Tanksley *et al.* 1989, Beckmann and Solter 1986).

Chemical composition of seed

Jatropha seed contains 22–40% oil, 4.7% polyphenol and 3.9% hydrocarbon. This semi-drying oil could be an efficient substitute for diesel fuel. The gross heat value for the seed (0% moisture content) was 4980.3 cal/g (20.85 MJ/kg), oil was 9036.1 cal/g (37.83 MJ/kg), and hydrocarbon was 9704.4 cal/g (40.63 MJ/kg). The oil fraction consists of both, saturated fatty acids, palmitic acid (14.1%), stearic acid (6.7%) and unsaturated fatty acids, oleic acid (47.0%), and linoleic acid (31.6%). Treatment of plants with growth regulators significantly influenced the production of hydrocarbons. Among the treatments, ethephon and morphactin induced the maximum production of hydrocarbon with 5.0% and 5.4%, respectively (Augustus *et al.* 2002). The fixed oil (41.5%) from the seeds was characterized for its fatty acid composition and physicochemical properties. The oil consisted of palmitic acid (14.16%), stearic acid (7.68%), oleic acid (46.72%) and linoleic acid (30.31%). The physico-chemical constituents were: refractive index (at 30°C) 1.4675, iodine value 102, saponification value 196.72, flash point 227°C and calorific value 8990 kcal/kg. The oil can be used as a mixed fuel for diesel/gasoline engines (Nasir *et al.* 1988).

Toxicity and edible *Jatropha*

Seven seed samples of *J. curcas*, in raw and roasted states, sold in some villages in Quintana Roo state, Mexico for human consumption were analyzed for physical characteristics, nutrients and anti-nutrients properties. The average seed weight varied from 0.53 to 0.74 g and kernel

weight as proportion of raw seed weight was from 61 to 66%. The contents of crude protein, lipid and kernel ash from raw seeds were 27–30, 55–62 and 3.7–5.2%, respectively. Anti-nutrients in meal from the raw seeds were: trypsin inhibitor activity (14.6–28.7 mg trypsin inhibited/g), lectin (25.6–52.2 unit; one unit is the reverse of minimum amount of mg meal/ml assay which produced haemagglutination), saponins (1.9–2.3% as diosgenin equivalent) and phytate (8.4–10%). Phorbol esters in kernels from raw seeds were not detected in four samples and in another three samples and it ranged from 0.01 to 0.02 mg/g as phorbol-12-myristate 13-acetate equivalent. Roasting of seeds inactivated almost 100% of trypsin inhibitor activity. Although lectin activity reduced on roasting but it was still present in high amounts. Saponins, phytate and phorbol esters were not affected by roasting (Makkar *et al.* 1998). Eighteen different provenances of *J. curcas* from Cape Verde, Senegal, Nigeria, Ghana, Benin, Burkina Faso, Kenya, Tanzania, Mexico, Nicaragua, Costa Rica, Burma and India were characterized for nutrient and antinutritional properties. The mean seed weight of the 18 provenances was 0.64±0.10 g. The kernel forms a large proportion of the seed and accounts for 61.3±3.1%. There were large variations in the contents of crude protein (19–31%; 26.0±3.2%), lipid (43–59%; 53.0±4.8%), neutral detergent fibre (3.5–6.1%; 5.0±0.87%) and ash (3.4–5.0%; 4.2±0.52%) in kernels. The gross energy of kernels was relatively similar (28.5–31.2 MJ/kg; 30.1±0.80 MJ/kg). Trypsin inhibitor activity in the defatted kernels (meal) varied from 18.4–27.5 mg of trypsin inhibited/g. Similarly, a wide variation was observed for saponins (1.8%–3.4% as diosgenin equivalent), phytate (6.2%–10.1% as phytic acid equivalent) and lectin activity in the meals. Tannins, amylase inhibitor, glucosinolates and cyanogens were not detected in any of the meals. Phorbol esters were not detected in the seeds collected in Papantla, Mexico, whereas the level of phorbol esters in the remaining 17 provenances ranged from 0.87 to 3.32 mg/g kernel (Makkar *et al.* 1997).

Investigations have shown that its residue contains toxic compounds and cannot be used as animal feed without further processing. Toxic substances present in the seeds are lectin and phorbol esters, due to which the seed cake is non edible but it is rich in nutrients. The protein content of the seed is about 68%. However, the seed meal from *Jatropha* varieties must be detoxified. Palatability trials on goats and sheep and digestibility trials on lamb with *Jatropha* meal and deoiled cake are going on for last three years at AICRP on Agroforestry Centre at Kattupakkam, Tamilnadu, preliminary results are encouraging.

Byproducts of *Jatropha*

Jatropha plantation provides many other products such as manure for the crops, methane for power generation and glycerol for industrial use besides, it may provide enormous advantage of carbon trading in future. The fruit pulp and the

remaining de-oiled seed cake can be used for the production of biogas by anaerobic fermentation. Slurry from biogas plant can further be processed as manure. The slurry of the bio gas plant can be mechanically separated into concentrate of rich nutrients for using in plantation. The dried out slurry forms manure for the agricultural use. Both these products can provide a major substitute to chemical fertilizers and pesticides. Cake has also a great potential of providing additional bioenergy in the form of electricity and biogas, fertilizer and pesticide. Byproducts from Jatropha processing, are increasingly being used in modern industry for cosmetics, varnishes and paints, lubricants, resins, adhesive, dyes and inks, pesticides, etc. These byproducts can make Jatropha plantation and biodiesel production a low risk venture.

Performance in diesel engine

The potential of oil from seeds of *J. curcas* as a diesel fuel substitute and agronomic research has established the feasibility of jatropha oil production since 1985 in Burkina Faso. Trans-esterification using ethyl alcohol has been applied to reduce oil viscosity and fuel properties of the raw oil and esterified product have been compared with other seed oil and diesel fuels. Successful short-term experiments to determine diesel engine performance showed that jatropha oil ethyl ester produced 81% of the maximum power, 86% of the maximum torque and 115% of the specific fuel consumption rate of diesel fuel No.2. No distinction could be made between the superiority of either jatropha or rapeseed oils as alternate fuels (Ouedraogo *et al.* 1991).

Performance, 50-hr continuous and starting tests were conducted using trans-esterified curcas oil, No. 2 diesel fuel, and their blends in two small pre-combustion chamber type diesel engines. Compatibility of engine parts to *J. curcas* oil was examined by submerging the parts in engine oil for 130 days. Blended oil produced superior thermal efficiency and fuel consumption equivalent to No. 2 diesel. There was a slight reduction in black smoke concentration when operating on transesterified *J. curcas* oil and its blended oils. The CO and HC concentrations from transesterified *J. curcas* oil increased at light loads and was equivalent to No. 2 diesel at full load. The HC concentrations of No. 2 diesel increased greatly at overload, while those of transesterified *J. curcas* oil decreased (Ishii and Takeuchi 1987).

An analysis of oil contents, physico-chemical properties, fatty acid composition and energy values of seed samples of four species of Jatropha (*J. curcas*, *J. glandulifera*, *J. gossypifolia* and *J. multifida*) revealed that the energy value of *J. multifida* oil was highest (13.647 kcal/g). All the oil samples were rich in oleic and linoleic acids (72.2–84.0%). However, no correlation between the energy values and fatty acid composition could be obtained (Banerji *et al.* 1985).

Economics

Although a lot is said about the minimum input cost of

Table 3 Economics of Jatropha cultivation–input costs

Expenditure	Unit/ha	Rate (₹)	Total (₹)
Planting material and overheads	2 500	5.0	12 500
Manure and fertilizer	3 000	1.0	3 000
Labour and other	300	20.0	6 000
Irrigation, weeding	3 000	1.0	3 000
Total			24 500

Source: Authors' calculation

Table 4 Average seed production expected during different year

Year after planting	Expected yield (kg /ha)	
	Rainfed crop	Irrigated crop
1st		250
2nd	250	1 000
3rd	1 000	2 500
4th	2 000	5 000
5th	3 000	8 000
6th and onwards	4 000	12 000

Source: Patil and Singh 1991

Jatropha plantation, the reality is often different. In fact only a well-maintained Jatropha plantation gives good returns. The inputs vary with the condition of site and labour wages. A moderate estimate is given in Table 3.

The returns of Jatropha vary with and without irrigation, although it grows well in un-irrigated land. The productivity however, is substantially higher in irrigated land. Seed yield estimated during different years under rainfed and irrigated condition by Patil and Singh (1991) is given here.

The returns are definitely higher from irrigated land. However, the returns from un-irrigated wasteland are also substantial, considering the fact that such land normally provides no returns. Mandal (2005) worked out the economics of Jatropha (Table 5). However, the economics and viability of the *Jatropha* plantation and biofuel

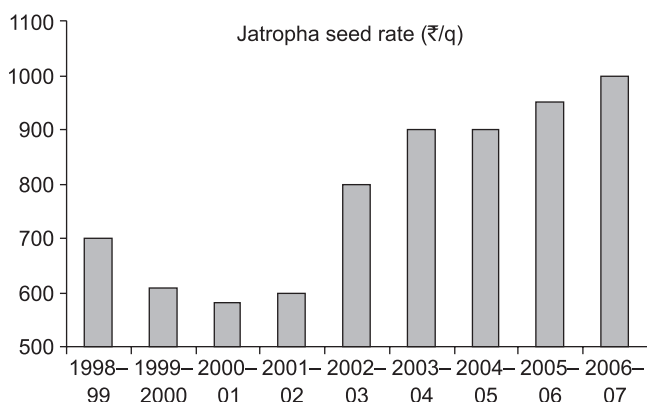


Fig 1 The *mandi* rates of Jatropha seeds at Dahod, Gujarat

Table 5 Cost of production/litre of biodiesel from Jatropha

Item	Cost (₹)	Assumptions/remarks
Cost of seed (₹/kg oil)	16.4	Seed ₹ 5/kg, oil yield 33%, 3.28 kg seed → 1 kg oil
Cost of collection and oil extraction	2.48	Losses 5%, 1.05 kg → 1 kg oil, cost @ ₹ 2.36/kg
Transesterification cost	6.67	For 300 tonnes/day plant
Cost of biodiesel/kg	25.55	
Less byproduct (oilcake)	-2.23	2.23 kg cake @ ₹ 1/kg
Less byproduct (glycerol)	-3.8	0.095 kg @ ₹ 40/kg
Net cost of biodiesel/kg	19.52	As per Planning Commission
Net cost of biodiesel/litre	16.59	Specific gravity of oil—0.85
Sale price of biodiesel to oil companies/litre	20	Profits @ 12% (₹ 2/l), transport @ ₹ 0.41/l and interest/misc. @ ₹ 1/l
Cost of petrodiesel/litre	18	(excluding excise/sales tax) Excluding excise/sales tax (based on \$50/barrel crude)

production are still at initial stage and will be governed by international market prices of crude oil as well as Government policies (NRCAF 2007).

Market of Jatropha

Till very recently, marketing of Jatropha was limited. However, since its promotion as a biofuel crop, market is developing for its seed. Among the various *mandis*, Jatropha seeds are most traded in Dahod *mandi* of Gujarat. The *mandi* rates for Jatropha, which can be seen to be much lower than the prevalent market rates (Fig 1). Current support price of Government is ₹ 8/kg.

R&D efforts

Presently more than 30 organizations including few private firms and NGOs are working on Jatropha R&D in India. Majority of them are working on evaluation of

germplasm for its improvement, and standardization of location-specific plantation techniques. Others are working on oil extraction and esterification machinery development, analyzing physico-chemical properties of oil and assessing the efficiency of biodiesel in motor vehicles and railway locomotives. Regional Research Station of Gujarat Agriculture University at Sardar Krushinagar has identified a variety named as 'Chatrapati' (SDAUJ 1) for cultivation in semi-arid region.

Directorate of Oilseed Research, Hyderabad has identified six accessions of the species, viz DORJC 54, 56, 57, 71, 73 and 74 as ideal biodiesel types based on high octane number. CSIR with collaboration of a German university has initiated a project on the basis of public-private partnership for testing IC Engine using Jatropha oil. NRC for Agroforestry, Jhansi has collected 284 germplasm of *J. curcas* from nine states, evaluating them for seed yield and oil content, standardizing

Table 6 Jatropha germplasm being evaluated at SAUs and NRCAF, Jhansi

Research centre	Total no.	Year of collection	Place of collection	Oil content (%)
NRCAF, Jhansi	284	2003, 2004 2005, 2006	Uttarakhand, Uttar Pradesh, Madhya Pradesh, Rajasthan, Gujarat, Maharashtra	22.79–40.31 32 accessions with >35% oil
CCS, HAU, Hissar	367	2003, 2005 2006	J&K, Himachal Pradesh, Punjab, Haryana, Uttar Pradesh, Gujarat, Rajasthan, Madhya Pradesh, Tamil Nadu, Maharashtra, Chattishgarh, Andhra Pradesh	30.8–34.7
PAU, Ludhiana	72	2004, 2005	Throughout country	20–33
YSPUHF, Solan, Himachal Pradesh	30	2004	Himachal Pradesh	25–35
College of Agriculture, Nagpur	10	2005	Maharashtra	
TNAU, Coimbatore	19	2005	Tamilnadu, Gujarat	28–35
ARS, Fatehpur, Rajasthan	20	2005	Rajasthan	
UAS, Dharwad	25	2005	Madhya Pradesh, Karnataka, Tamil Nadu, Maharashtra	
IGAU, Raipur, Chhattisgarh	31	2004, 2005	Central and East India	31–48
SDAU, SK Nagar, Gujarat	21	2004, 2005	Throughout country	31.7–43.5
TFRI, Jabalpur, Madhya Pradesh	150	2004, 2005	Madhya Pradesh, Maharashtra	18.2–35
MPKV, Rahuri, Maharashtra	23	2004, 2005	Madhya Pradesh, Karnataka, Maharashtra	10.8–42.90
SKUAS&T, Jammu	23	2004, 2005	Jammu and Kashmir and other states	32–35

Source: NOVOD 5th R&D report on TBOs and AICRPAF, Jhansi report on TBOs

its management practices including agrotechniques, molecular characterization and hybridization. The Centre has identified four promising genotypes which are undergoing multi-location trials. GBPUAT, Pant Nagar; JNKV, Jabalpur; and CRIDA, Hyderabad are working on plantation stand establishment, silviculture and management aspects of *Jatropha*. CAZRI, Jodhpur has reported that selected lines of the species collected from Rajsamand district of Rajasthan, are drought tolerant. Indian Institute of Petroleum, Dehradun, CSMRI, Bhavnagar and NBRI, Lucknow are engaged in hydrocarbon recovery from *Jatropha* oil and conversion into liquid fuel.

Breeding and improvement programme

R&D programme by ICAR: Indian Council for Agricultural Research (ICAR) started *Jatropha* improvement programme in 2003 through a network of selected centres of State Agricultural Universities and centres of ICAR. A total number of 827 germplasm have been collected from different parts of the country and being evaluated for growth performance, seed yield and oil content at different locations (Table 6). It may be noted that initially a number of centres have reported very high seed yield and oil contents but the same could not be confirmed afterwards.

There is a large variation in its seed yield from the experimental germplasm evaluation trials going on in different parts of the country. At National Research Centre for Agroforestry, Jhansi, from 530–653 g/plant seed yield of some accessions was obtained in third year under rainfed condition. The low yield of the accessions is also attributed to acute drought situation in Bundelkhand region where the Centre is located. The region experienced continuous drought from 2004–2007. However, the yield is quite high from hybrids during 2010 (1.2–1.8 kg/plant). Yield performance of different germplasm at NRCAF, Jhansi is given in Table 7.

R&D programme by NOVOD Board: The national network R&D programme of NOVOD Board is going on at 61 research institutions. Major components are identification of elite planting material, seed resource assessment, collection and storage, phenological and chemical evaluation for characterization, etc. All the participating institutes have collected a total of 3 291 accessions of selected plants of *Jatropha* and 1 284 accessions of karanja.

R&D programme by DBT, GOI, and CSIR: DBT started *Jatropha* Micro-mission in 2005–06 by involving 15 institutions of different state and national level. Under this programme a total of 1 484 *Jatropha* germplasm has been collected and being evaluated in field over 692.74 ha area on 145 locations for growth and yield. CSIR institutes in different parts of the country have collected a total of 186 accessions from 15 states of country under *Jatropha* Project Network and evaluating them for oil content and seed yield in field conditions.

Promising germplasm identified for Jatropha cultivation by MNRE, Government of India: In recent past, Ministry of New and Renewable Energy (MNRE) organized a series of meetings with members from DRDO, ICAR, CSIR, DBT and industries on screening and identification of elite germplasm and finally a list of promising germplasm available with the host institutions has been prepared by it (Table 8).

Limitations of the crop

Low seed yield: In general presently, the seed yield of the crop is low except a few germplasm, may be due to poor management in respect of spacing, nutrition, irrigation and pruning levels associated with un-adapted provenances. Standardization of nursery, silvicultural techniques, breeding and selection of high-yielding genotypes can solve this problem.

Table 7 Yield performance of *Jatropha* germplasm at NRCAF, Jhansi

Progeny trial	Genotype tested	Spacing (m)	Potential genotypes	Seed yield / plant (g)	Seed oil content (%)	Yield (tonnes/ha)
Progeny trial (August 2004)	27	2×2	NRCJ 2	530.0 (4th year)	35.12	1.3
			NRCJ 7	653.2	34.17	1.6
			NRCJ 12		33.12	1.4
Progeny trial-I (August 2005)	23	3×3	NRCJ 52	302.25 (3rd year)	35.10	0.3
Progeny trial-II (August 2005)	9	3×3	NRCJ 68	360.75(3rd year)	31.50	0.4
			NRCJ 64	320.80	32.90	0.4
Progeny trial-III (August 2005)	12	4×3	NRCJ 89	682.00 (3rd year)	30.50	0.6
			NRCJ 91	585.00	35.15	0.5
Progeny trial-IV (August 2006)	87	3×3	NRCJ 97	840.5 (2nd year)	33.10	0.9
			NRCJ 168	682.5	36.16	0.8
			NRCJ 82	530.4	30.51	0.6
			NRCJ 87	507.9	29.85	0.6

Source: NRCAF field experiment results

Table 8 List of promising germplasm prepared by MNRE, Government of India

Genotype	Seed oil (%)	Yield/plant (g)	Condition
<i>North-western hills zone</i>			
*DARL 1	34.4	220 (2nd yr)	Rainfed/semi irrigated
*DARL 2	36.5	240 (2nd yr)	
<i>North and north-western plains (Uttar Pradesh)</i>			
*** JA 126	37.2	1000 (3rd yr)	For wasteland
*** JA 135	37.0	2000 (3rd yr)	
*** Pant J Sel-2	34.0	320 (3rd yr)	
<i>Semi-arid zone (Madhya Pradesh, Maharashtra and Andhra Pradesh)</i>			
*DARL 1	34.4	220 (2nd yr)	Rainfed/semi irrigated
*DARL 2	36.5	240 (2nd yr)	
#NRCJ 08-4	37.6	334.1 (2nd yr)	
#NRCJ 08-6	36.1	583.0 (2nd yr)	
** NBRI UP-Luck-1004-J-18	35.2	237.8 (2nd yr)	
** CRIDA AP-Adila-904-JL-06	35.2	250.1 (2nd yr)	
<i>Arid zone (Gujarat and Rajasthan)</i>			
# PAPL JPH009	37.7	102 (3rd yr)	Semi irrigated Arid
** CP 9	36.5	1800 (3rd yr)	Semi Arid
<i>South zone (Tamilnadu)</i>			
*** MSSRF (560687)	30.6	1420.0 (2nd yr)	Rainfed/Semi irrigated
*** MSSRF (560688)	30.6	1270.0 (2nd yr)	
<i>North-eastern zone</i>			
# NE-2 MNJ002 (Manipur) IC 565939	38.6	123.0 (2nd yr)	
# NE-6 Ribhoi- Mawhati IC 565942	38.4	286.8 (2nd yr)	

Total number of promising genotypes from different organizations: * DRDO = 02, ** CSIR = 04, *** DBT = 04, **** GBPUA&T, Pantnagar = 01, # ICAR = 04, Others = 02; Source: MNRE, Meeting Reports 2009

Low oil content

In general *Jatropha* contains about 30–35% oil, which is low for commercial extraction. The maximum oil is stored in the cotyledons, which has maternal inheritance, and hence, improvement in this trait through hybridization are lesser than the selection of high-yielding lines having high oil content. Therefore, extensive survey and selection of high yielding lines can increase oil content. By exploring the genetic diversity through molecular techniques can also help in resolving this problem.

Summary and conclusion

Jatropha research is still at the beginning with respect to genetic improvement for increasing seed and oil yield. A good beginning has been made on collection and selection in local germplasm, and germplasm from 110 districts of the country has been collected by the different centres. Due to xenogamy, wide adaptability and distribution to such a large geographical area, there is enough possibility of genetic variation in this species. High variability provides good opportunity for selection of desired types and success in breeding programme. This will get further boost if the researcher has access to the global germplasm. For this an adequate mechanism has to be made through CGAIR institutions. Simultaneously, attempts may be made to develop intra-specific crosses to exploit the hybrid vigour. The variety/hybrid thus developed can be used for large-scale plantation

across the country. Besides, genetic improvement using conventional breeding approaches has to be initiated at a number of centres in network mode and integrated with latest biotechnological techniques for reducing time and increasing efficiency of breeding. The focus should be on development of synthetic/composite high-yielding variety and inbred lines for development of hybrids with broader genetic base having good adaptability, resistance to pest and disease with stable performance over the locations. Evaluation and characterization of *Jatropha* breeding material using molecular breeding techniques and mass multiplication of elite lines of *Jatropha curcas* through tissue culture for large scale plantation needs to be taken on priority.

Since, the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA) has been established under the Protection of Plant Varieties and Farmers' Rights Act, 2001. Improved material can be registered now to protect plant breeders' rights. A beginning has been made by development of Network Project for DUS Testing on *Jatropha* and karanj (*P. pinnata*) at the NRCAF. This will lead to identification of promising varieties for registration in PPV&FRA, New Delhi.

REFERENCES

- Alam B, Kumar R V and Rathakrishnan P. 2009. Studies on augmenting pistillate flowers in *Jatropha curcas* L. *Annual*

- Report, 2009, 42 pp. NRCAF, Jhansi
- Augustus G D P S, Jayabalan M and Seiler G J. 2002. Evaluation and bioinduction of energy components of *Jatropha curcas*. *Biomass and Bioenergy* **23** (3): 161–4.
- Banerji R, Chowdhury A R, Misra G, Sudarsanam G, Verma S C and Srivastava G S. 1985. *Jatropha* seed oils for energy. *Biomass* **8** (4): 277–82.
- Beckmann J S and Soller M. 1986. Restriction fragment length polymorphisms in plant genetic improvement. *Oxford Surv. Plant Molecure Cell Biology* **3**: 197–50.
- Basha S D and Sujata M. 2009. Genetic analysis of *Jatropha* species and the interspecific hybrids of *Jatropha curcas* using nuclear and organelle specific markers. *Euphytica* **168**: 197–214.
- Bhattacharya A, Datta K and Datta S K. 2005. Floral biology, floral resource constraints and pollination limitation in *Jatropha curcas* L. *Pak Journal of Biological Science* **8** (3): 456–60.
- Bhattacharya, P. and Joshi, B. 2006. Strategies and institutional mechanism for large scale cultivation of *Jatropha curcas* under agroforestry in the context of proposed biofuel policy of India. *ENVIS Bull. Grassland Ecosystem & Agroforestry* **1**: 58–72.
- BP Statistical Review of World Energy. 2008. www.bp.com/statisticalreview.
- Chang-wei L, Kun L, You C, Yong-yu S and Wen-yun Y. 2007. Pollen viability, stigma receptivity and reproductive features of *J. curcas* L. (Euphorbiaceae). *Journal of Northwest Nafive Plants*. **27** (10): 1994–2001.
- Chaudhari D C and Joshi D N. 1999. *Jatropha curcas*: a multipurpose species for economic prosperity and wasteland development. *Advances in Plant Sciences Research in India* **9**: 35–9.
- De Chelmicki J C C and De Varnhagen F A. 1841. *Geografia Cabo Verdiana on Descripc,ão Geografico – Historica da Prov. das Ilhas de Carbo Verde e Guiné. Vol. 1, 2*. Typ. by L. C. da Cunha, Lisboa (Portugal).
- De Avila J. G. 1949. *Breves Instruc,ões para a Cultura da Purgueira. (in) Repartic,ão Tecnica dos Servic,os Agricolas, Florestais e Pecuários*. Imprensa Nacional de Cabo Verde, Praia (Cape Verde).
- Dhillon R S, Hooda M S, Handa A K, Ahlawat K S, Kumar Y Subhash. 2006. Clonal propagation and reproductive biology in *Jatropha curcas* L. *Indian Journal of Agroforestry* **8**(2) :18–27.
- Dhillon R S, Hooda M S, Pundeer J S, Kumari S. 2009a. Development of efficient techniques for clonal multiplication of *Jatropha curcas* L., a potential biodiesel plant. *Current Science* **96** (6): 823–7.
- Dhillon R S, Hooda M S, Jattan N, Chawla V, Bhardwaj M and Goyal S C. 2009b. Development of molecular characterization of interspecific hybrids of *Jatropha carcass* and *J. integerrima*. *Indian Journal of Biotechnology* **8**: 384–90.
- Dhyani S K, Ram Newaj and Sharma A R. 2009. Agroforestry: its relation with agronomy, challenges and opportunities. *Indian Journal of Agronomy* **54**(3): 249–66.
- IARI 2007. Progress report on Economic Analysis and Prospects of Non-edible Oilseeds in India. IARI, New Delhi.
- Ishii Y and Takeuchi R. 1987. Transesterified curcas oil blends for farm diesel engines. Transactions of the ASAE. *American Society of Agricultural Engineers* **30** (3): 605–9.
- Jadhav B B, Khadatar B S, Shinde V V and Chavan S A. 1995. Performance of differently spaced *Jatropha curcas* under fertilizer management in Konkan region of Maharashtra. *Journal of Maharashtra Agricultural Universities* **20** (1): 24–6.
- Jyoti S, Amla B, Renu S, Sardana J, Batra A and Sharma R. 1998. *In vitro* plantlet formation and micropropagation of *Jatropha curcas*(L.). *Advances in Plant Sciences* **11**(2): 167–9.
- Jyoti S, Amla B and Ali D J. 2000. An expeditious method for regeneration of somatic embryos in *Jatropha curcas* L. *Phytomorphology* **50** (3–4): 239–42.
- Kaushik N, Deswal R P S and Sharma K D. 2001. Maturity indices in *Jatropha curcas*. *Seed Research* **29** (2): 223–4.
- Kumar R V and Swarnkar G K. 2003. Rooting response in stem cuttings of *Jatropha gossypifolia*. *Indian Journal of Agroforestry* **5** (1&2): 131–3.
- Kumar R V, Ahlawat S P, Handa A K and Gupta V K. 2004. *Jatropha curcas*: Fuel of future. *Employment News* (20–26 Nov.) Vol. **29** (34): 1–2.
- Kumar R V, Singh R, Ahlawat S P, Dar S H, Tripathi, Y K and Yadav V P. 2005. Evaluation of genetic divergence in accessions of *Jatropha curcas* L. *Journal of Tropical Forestry* **21** (3&4): 34–40.
- Kumar R V, Tripathi, Y K, Yadav V P and Ahlawat S P. 2007. Study on laccase, peroxidase, cellulose and polyphenol oxidase enzyme activity in *Jatropha curcas* L. *Indian Journal of Agroforestry* **9** (1): 42–6.
- Kumar R V, Tripathi, Y K, Yadav V P, Ahlawat S P and Gupta V K. 2008a. Oil percentage in *Jatropha curcas* L. germplasm of national repository. *Indian Journal of Genetics and Plant Breeding* **69–8** (4): 463–6.
- Kumar R V, Tripathi, Y K, Ido Izhaki, Yadav V P and Ahlawat S P. 2008b. Intraspecific variation and interrelationships between morphology, nutritional content and enzymatic activity of *Jatropha curcas* L. *Current Science* **95** (2): 239–43.
- Kumar R V, Tripathi, Y K, Shukla P, Ahlawat S P and Gupta V K. 2009. Genetic diversity and relationship among germplasm of *Jatropha curcas* L. revealed by RAPDs. *Trees* **23**: 1075–9.
- Kureel R S. 2007. Biofuels: Global and Indian Scenerio- Policy Perspective. *4th International Biofuels Conference*, held at New Delhi, during 1–2 February 2007.
- Laila H M and Zarad S S. 1994. A preliminary evaluation of some growth parameters of purging nut (*Jatropha curcas*) seedlings grown in different soil mixtures. *Annals of Agricultural Science* **39** (2): 781–9.
- Levingston R and Zamora R. 1983. Medicine trees of the tropics. *Unasylva* **140**: 7–10.
- Liu H F, Kirchoff B K, Wu G J and Liao J P. 2007. Microsporogenesis and male gametogenesis in *Jatropha curcas* L. (Euphorbiaceae). *Journal of Torrey Botanical Society* **134** (3): 335–43.
- Makkar H P S, Becker K, Sporer F and Wink M. 1997. Studies on nutritive potential and toxic constituents of different provenances of *Jatropha curcas*. *Journal of Agricultural and Food Chemistry* **45** (8): 3152–7.
- Makkar H P S, Becker K and Schmook B. 1998. Edible provenances of *Jatropha curcas* from Quintana Roo state of Mexico and effect of roasting on antinutrient and toxic factors in seeds. *Plant Foods for Human Nutrition* **52** (1): 31–6.
- Makwana V, Shukla P and Robin P. 2010. GA application induces alteration in sex ratio and cell death in *Jatropha curcas*. *Plant Growth Regulation* **61**: 121–5.

- Mandal R. 2005. Energy—alternate solutions for India's needs: biodiesel. Planning Commission, Government of India, New Delhi.
- Martin G and Mayeux A. 1984. *Reflèxions sur les cultures oléagineuses energetiques. 2. Le pourghère (Jatropha curcas L.): Un carburant possible. Oléagineux* 39: 283–7.
- Narain S and Watna S. 1983. Effect of IBA on root formation of stem cutting of purging nut (*Jatropha curcas* L.) Bangkok (Thailand) 19 leaves.
- Nasir M K A, Memon G M, Valhari M U and Khatri L M. 1988. Studies on fixed oil of *Jatropha curcas* seeds. *Pakistan Journal of Scientific and Industrial Research* 31 (8): 566–8.
- NRCFAF 2007. *Perspective Plan- Vision 2025*, 46 pp. National Research Centre for Agroforestry, Jhansi.
- Ouedraogo M, Ayers P D and Linden J C. 1991. Diesel engine performance tests using oil from *Jatropha curcas* L. *Agricultural Mechanization in Asia, Africa and Latin-America* 22 (4): 25–9.
- Pandey R K and Datta S K. 1995. Gamma ray induced cotyledonary variabilities in *Jatropha curcas* L. *Journal of Nuclear Agriculture and Biology* 24: 62–6.
- Pandey R K, Datta S K and Mishra P N. 1998. Performance of mutagen treated *Jatropha curcas* (petro-crop) on alkali soil. *Journal of Nuclear Agriculture and Biology* 27: 165–71.
- Partibhan K T, Kumar R S, Thiyagarajan P, Subbulakshmi V, Vennila S and Govinda Rao M. 2009. Hybrid progenies in *Jatropha* – a new development. *Current Science* 96 (6): 815–23.
- Paterson A H. 1996. (in) *Genome Mapping in Plants*, pp 71–83. Paterson AH (Ed.), RG Landes Company and Academic Press, Inc. Texas, USA.
- Patil V and Knawarjit Singh. 1991. *Oil Gloom to Oil Boom Jatropha curcas : A Promising Agroforestry Crop*. 82 pp. Agroforestry federation Maharashtra and National Wasteland Development Mission, MoEF, GOI.
- Patil V, Singh K and Bhandari T N. 2003. *Experience and Observations about Jatropha Plantations (1986–2003)*, pp 2–10. Agroforestry and Wasteland Development Foundation, Nasik.
- Planning Commission 2003. *Report of the Committee on Development of Bio-Fuel*. Government of India, New Delhi.
- Prabakaran A J and Sujatha M. 1999. *Jatropha tanjorensis* Ellis & Saroja, a natural interspecific hybrid occurring in Tamil Nadu, India. *Genetic Resources and Crop Evolution* 46 (30): 213–8.
- Prakash A R, Patolia J S, Chikara J and Boricha G N. 2007. Floral biology and flowering behaviour of *Jatropha curcas*. (in) *Expert Seminar on Jatropha curcas L. Agronomy and Genetics*, March 26–28. Wageningen, The Netherlands: Publisher FACT Foundation.
- Qing Y, Ping P D, Biao D Z, Liang W Z and Xiang S Q. 2007. Study on pollination biology of *Jatropha curcas* (Euphorbiaceae). *Journal of South China Agricultural University* 28 (3): 62–6.
- Raina A K, and Gaikwad B R. 1987. Chemobotany of *Jatropha* species in India and further characterization of “Curcas oil”. *Journal of the Oil Technologists Association of India* 19 (4): 81–5.
- Rajore S, Sardana J, Amla B and Batra A. 2002. *In vitro* cloning of *Jatropha curcas*. *Journal of Plant Biology* 29 (2): 195–8.
- Raju A J S and Ezradanam V. 2002. Pollination ecology and fruiting behaviour in a monoecious species, *Jatropha curcas* L. *Current Science* 83 (11): 1395–8.
- Rathakrishnan R and Paparamathma M. 2009. potentials and *Jatropha* wealth of India. *Current Science* 97: 1000–4.
- Ram Newaj and Dhyani S K. 2008. Agroforestry for carbon sequestration: Scope and present status. *Indian Journal of Agroforestry* 10(1): 1–9.
- Shanker Chitra and Dhyani S K. 2006. Insect pests of *Jatropha curcas* L. and the potential for their management. *Current Science* 91: 162–3.
- Shukla S K. 2005. Experiences of Chattisgarh biofuel development authority. *Biofuels India* 3(4): 12–3.
- Sujatha M and Dhingra M. 1993. Rapid plant regeneration from various explants of *Jatropha integerrima*. *Plant Cell, Tissue and Organ Culture* 35 (3): 293–6.
- Sujatha M and Mukta N. 1996. Morphogenesis and plant regeneration from tissue culture of *Jatropha curcas*. *Plant Cell, Tissue and Organ Culture* 44 (2): 135–41.
- Staubmann, R, Ncube I, Gubitza G M, Steiner W and Read J S. 1999. Esterase and lipase activity in *Jatropha curcas* L. seeds. *Journal of Biotechnology* 75: 2–3.
- Tanksley S D & McCouch S R. 1997. Seed banks and molecular maps: unlocking genetic potential from the wild. *Science* 277: 1063–6.
- Tanksley S D, Young N D, Paterson A H & Bonierbale M W. 1989. RFLP mapping in plant breeding. New tools for an old science. *Biotechnology* 7: 257–64.
- Wani, S P, Sreedevi, T K, Reddy, B V S. 2006. Biofuels: status, issues and approaches for harnessing the potential. Hyderabad, India. <www.indianjournals.com/ijor.aspx?target=ijor:in&volume=3and4&issue=4and1&article=004>.