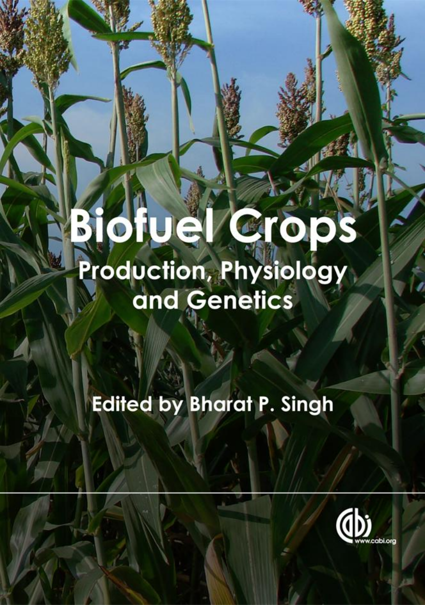

Biofuel Crops

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Bharat P. Singh

Fort Valley State University
Fort Valley, Georgia
USA

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CABI
Nosworthy Way
Wallingford
Oxfordshire OX10 8DE
UK

Tel: +44 (0)1491 832111
Fax: +44 (0)1491 833508
E-mail: info@cabi.org
Website: www.cabi.org

CABI
38 Chauncey Street
Suite 1002
Boston, MA 02111
USA

Tel: +1 800 552 3083 (toll free)
Tel: +1 (0)617 395 4051
E-mail: cabi-nao@cabi.org

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15 Jatropha (*Jatropha curcas* L.)

Suhas P. Wani
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India

15.1 Introduction

Biodiesel is an important renewable biofuel that offers great potential to ease and mitigate energy shortage, supplement/replace fossil fuel while at the same time minimize/reduce carbon emissions. Biodiesel production is expanding rapidly because of demand, necessary policy support and technological availability. However, shortage of raw material to produce biodiesel is a major constraint (Wani *et al*., 2006b). Oils from plants are the main source for the production of biodiesel. Of the 100–300 oil-bearing plant species, 30 hold promise for biodiesel production (Hegde, 2003). Many developed countries are using edible oilseed crops such as soybean, rapeseed, groundnut and sunflower for production of biodiesel. Biodiesel production from vegetable oils during 2004/2005 was estimated to be 2.36 Mt globally. Of this, EU countries (1.93 Mt with expectation of 30% annual increase) and the USA (0.14 Mt) together accounted for 88% and the rest of the world (0.29 Mt) for the remaining 12% (Parikh, 2005). However, for developing countries like India, having a huge shortage of edible oil (6.31 Mt year^{-1}) for consumption, there is no question of using edible oil as a source of biofuel.

The non-edible oilseeds such as pongamia (*Pongamia pinnata*) and jatropha (*Jatropha curcas*), which along with providing biodiesel can also meet the additional criteria of greening the wastelands without compromising the food, fodder security and improved livelihoods, are more suited as biofuel oil crops for developing countries (Wani *et al*., 2006a; Reddy *et al*., 2008). Jatropha, which meets the American and European biofuel standards, has gained importance in tropical and subtropical countries and has been promoted heavily (Tiwari *et al*., 2007). The committee on biofuels constituted by the Planning Commission, Government of India (2003), out of a large number of oilseed-bearing tree species identified jatropha and pongamia as potential candidates best suited to Indian conditions.

Jatropha (*Jatropha curcas* L.), commonly known as 'purging nut' or 'physic nut', is also referred to by various other names in different countries. The plant is naturally distributed in Mexico, Central America and parts of South America (Trabucco *et al*., 2010). Carried to different parts of the world by the Portuguese colonial power, jatropha now grows in many African and South Asian countries. Jatropha is a tropical, perennial, C_3 plant belonging to the family *Euphorbiaceae* (Tatikonda *et al*., 2009; Divakara *et al*., 2010). The plant is a deciduous tree with a succulent stem and leaves and a soft wood (Borchert, 1994; Foidl *et al*., 1996). It is adapted to semi-arid tropical conditions. As a plant of the dry regions of Meso-America, jatropha is suitable to grow on degraded drylands.

It has a liking for well-drained soils and is susceptible to collar rot disease in high rainfall humid areas or excessive irrigation or to waterlogging. It produces fruits with a high content of non-edible oil that can be used for several purposes. As with many members of the family *Euphorbiaceae*, it contains compounds that are highly toxic and is thus not browsed by livestock (Wani and Sreedevi, 2007).

15.2 Jatropha, a Wonder Plant – Myth or Reality?

The claim of jatropha being a wonder plant is based on its perceived ability to grow successfully in semi-arid environmental conditions and on degraded soils. Therefore a special deliberation on these features of the plant is presented below.

15.2.1 Drought tolerance

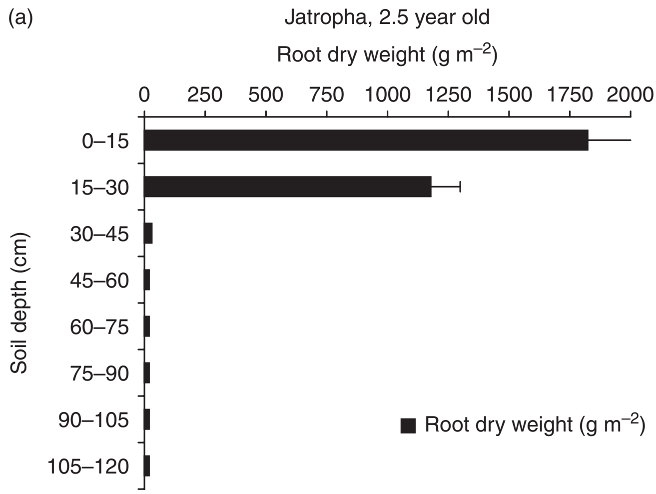
There is limited knowledge about the actual water requirement of jatropha in different agroecological regions. However, minimum and optimum rainfall to produce harvestable jatropha fruits has been assessed at 500–600 and 1000–1500 mm year^{-1} in arid and semi-arid tropics, respectively (Achten *et al.*, 2008; da Schio, 2010; Trabucco *et al.*, 2010).

Water use assessment of jatropha plantations in the semi-arid tropical location at ICRISAT (Indian Crop Research Institute for the Semi-Arid Tropics), Patancheru, India indicated that evapotranspiration (ET) under no moisture stress conditions varied from 1410 to 1538 mm year^{-1} during 2006–2009 (ICRISAT, 2010). Under the actual field conditions, the ET requirements varied from 614 to 930 mm depending on the atmospheric demand, rainfall and crop phenological stage. Patterns of soil water depletion indicated that the 2-year-old jatropha plantation was able to extract water up to a soil depth of about 100 cm and later at the age of 5 years it was able to extract up to 150 cm. Monthly water use of jatropha varied from 10 to 20 mm (leaf shedding period) to 140 mm depending on water availability and environmental demand (Kesava Rao *et al.*, 2012). Thus, contrary to the belief that jatropha needs less water, under favourable soil moisture conditions the tree could use large amounts of water for luxurious growth and high yield.

The low transpiration coefficients (0.51–0.60) of jatropha compared to that of a reference plant (0.51–0.70) and limited stem sap flow of 12-year-old adult trees in a semi-arid region of South Africa supports its conservative water use (Holl *et al.*, 2007; Achten *et al.*, 2010a). Jatropha can survive under 200 mm water year^{-1}. The extent and timing of its leaf drop is acutely influenced by drought (Maes *et al.*, 2009; Achten *et al.*, 2010a). The remaining plant leaves are known to exhibit paraheliionasty under drought stress as a drought response. Jatropha is also known to change the anatomy of the freshly produced leaves to suit the low water availability situations under drought. It is capable of rapid adjustment to drought or to escape drought well, but not continuously, nor is it equipped for high productivity under drought. Maes *et al.* (2009) are of the opinion that jatropha has evolved and adapted to plant survival under water-deficit environments rather than to maintain high levels of plant productivity under stress.

Jatropha root traits and their significance for drought tolerance

Root distribution of jatropha, both in terms of weight and length density, was recorded by Krishnamurthy *et al.* (2012) in the top 0–30 cm soil horizon. The highest root length density distribution was noted in the top 15 cm soil profile measuring close to 0.5 cm cm^{-3} of soil with decreasing root length density distribution to <0.1 cm cm^{-3} in deeper layers below 60 cm depth (Fig. 15.1). An exposed trench wall showed the rooting to extend up to 1.4 m (Fig. 15. 2). However, this is in contradiction to the descriptions quoted by Foidl *et al.* (1996) who observed four to five branches on a vertical taproot that penetrates up to 5 m deep under Nicaraguan conditions. The difference in findings of Foidl *et al.* (1996) from Krishnamurthy *et al.* (2012) could be due to enormous resistance to the root system growth under high soil bulk density of the red soil with heavy, compact and shallow murram layer below 60–75 cm soil depth where the



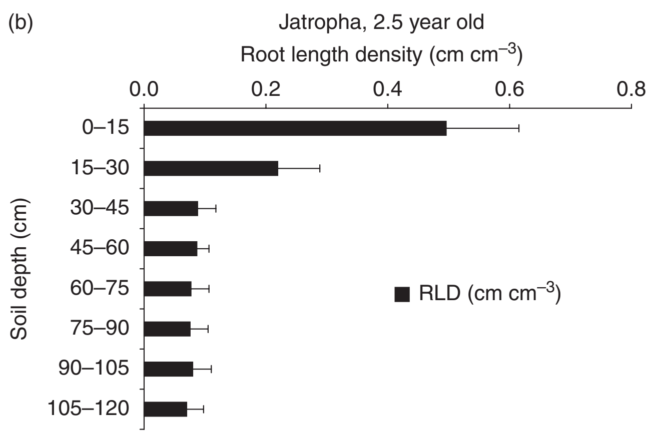


Fig. 15.1. The root distribution in jatropha as measured through a monolith method. Changes in (a) root dry weight across various soil depths and (b) in root length density across various soil depths in a 2.5-year-old plant. Such a large difference in distribution weight or length is primarily caused by the small section of taproot at the 0–30 cm soil horizon (Krishnamurthy *et al.*, 2012).

later experiment's root extraction was carried out. In annual crop plants such as wheat, a root length density greater than 0.5 cm cm^{-3} was estimated to be adequate for complete extraction of available soil water (Passioura, 1982). Though measurements of rooting depth and root length density need not necessarily give an estimated ability of the plant to extract soil water, still a root length density of <0.1 cm cm^{-3} in jatropha was found to be grossly sub-optimal. Root dry weight distribution up to the depth 0–30 cm accounted for almost all the roots of the jatropha plant. In deeper soils below 30 cm the root dry weights ranged from 21 to 2 g m^{-2}. Root length distribution was dense only in the surface soil regions.

The allocation of dry matter for root to shoot was 0.37, but this ratio was reduced to a mere 0.03 when the root weight of the taproot at the 0–30 cm soil depth was not included for this estimation, indicating that the major root biomass is distributed for the purpose of anchoring rather than for absorption of soil moisture or nutrients from the soil (Krishnamurthy *et al.*, 2012). Closely comparable values of root/shoot ratio, ranging from 0.41 to 0.27 depending on the soil water deficit regimes, had been reported for 104-day-old

LC7	LC6	LC5	LC4	LC3	LC2	LC1	C	RC1	RC2	RC3	RC4	RC5	RC6	RC7	
20	18	33	16	18	20	7	15	20	18	18	18	14	23	11	270
11	8	18	11	14	16	12	8	21	17	18	16	15	5	11	202
7	6	3	8	3	8	13	10	15	21	9	5	3	7	1	123
8	4	3	3	5	6	5	7	6	10	3	13	5	8	8	94
7	2	3	4	7	3	8	1	3	12	5	4	4	3	5	71
1	3	5	8	7	6	9	4	6	6	1	5	1	4	8	75
4	3	5	1	5	6		1	2	3	3	2	3	3	6	47
2				7	3	6			1		2	1	6	3	31
1	1	2		2				1			2	1			10
	1						3								4
1			1				3		1					1	7
		2					5	1						2	13
								1							1
					1	1									2

Fig. 15.2. The root distribution in jatropha as measured through a trench wall method. Number of root intercepts that were measured in a 10 cm soil horizon and across 150 cm (70 cm on either side of the plant's base). After exposing a trench wall close to the plant base, the wall was washed with a fine spray of water and the protruding roots were trimmed before recording the observations. Only a single plant root growth was measured for this purpose. C in the X scale means centre grid, LC_n means to the left of centre and RC_n to the right of centre. Each grid denotes the number of root intercepts within each 100 cm^2 grid and numbers on the right *y* axis are the total number of intercepts in each 10 cm soil horizon (Krishnamurthy *et al.*, 2012). Black, >10 intercepts per grid; dark grey, 5–10 intercepts per grid; medium grey, 3–4 intercepts per grid; light grey, 1–2 intercepts per grid.

jatropha seedlings by Achten *et al*. (2010b). These values were found to be the lowest compared with ten other tropical deciduous woody and shrub species (*Celaenodendron mexicanum* Standl, *Trichilia trifolia* L., *Caesalpinia eriostachys* Bench, *C. platyloba* S. Wats, *Plumeria rubra* L., *Apoplanesia paniculata* Presl., *Cordia alliodora* (Ruiz & Pav.) Oken, *Cochlospermum vitifolium* (Willd) Spreng, *Ipomoea wolcottiana* Rose, *Heliocarpus pallidus* Rose (Huante and Rincon, 1998)). Under extreme drought, jatropha started shedding its leaves and stopped growing (Achten *et al*., 2010b). For a perennial growth habit and for a shrub, the root system distribution in jatropha is shallow, root proliferation poor and root biomass allocation to the absorbing roots meagre. But the roots were found to be well equipped for rapid branching whenever growth opportunity arose after rain and adapted for absorbing minerals from highly secluded pockets of soil. Krishnamurthy *et al*. (2012) found that under conditions of water replenishment the lateral root growth quickly resumed because of the large number of branch primordia on the thicker roots.

Krishnamurthy *et al*. (2012) observed the presence of a limited number of narrow xylem vessels and a well-defined cortex in jatropha indicative of potentially slow absorption of water needed to conserve soil water under drought. Therefore it can be concluded that jatropha has a relatively small root system for a tree to be a good producer under limited soil conditions but a xylem vessel system that enables it to survive under drought.

15.2.2 Jatropha plantations' impact on hydrological processes

Evaluation of how downstream hydrological processes and sediment transport at the mesoscale (10–10,000 km^2) will be affected by large-scale jatropha planting is so far lacking. Even so, from the perspective of water, jatropha cultivation is considered an option for making productive use of wastelands while at least partly avoiding conflicts with downstream environmental flow requirements. Beneficial effects such as less erosive storm floods and lower sediment loads in riverine ecosystems, and larger groundwater formation as a result of improved infiltration is envisioned (Garg *et al.*, 2011).

Water balance

The water balance differs substantially depending on land use and amount of annual average rainfall (Fig. 15.3a). In general, a larger share of the total rainfall forms runoff during wetter years compared with drier years. A comparison of the different land management scenarios showed that more than 50% of the non-productive soil evaporation in the wasteland was shifted into productive transpiration in the case of both current and long-term jatropha plantations. The total amount of ET was relatively similar in all three cases, except during dry seasons when ET was higher in current jatropha plantation than wasteland, and increased further under improved soil conditions in the long-term plantation. Groundwater recharges doubled in the current and quadrupled in the long-term plantation compared to the wasteland. As a result of higher ET and groundwater formation, runoff decreased in the jatropha plantings, in particular during dry years. In the case of wasteland, runoff constituted around 40% of the total rainfall during dry years while the corresponding figure for the current jatropha plantation was around 30%, and even lower (down to 20%) for the long-term plantation. Such a large reduction in outflows from the watershed at a time when the average rainfall amount is low might have negative impacts on downstream ecosystems and water users.

The distribution of the water balance components within the year also varied with land use (Fig. 15.3b). While the total ET was lower for the two jatropha plantations during the dry season (December–March), it became higher during the wetter parts of the year. This means that the annual fluctuations in runoff and groundwater generation are smaller in the jatropha plantations compared with the wasteland.

Runoff generated from the watershed consists of two components: (i) surface runoff; and (ii) base flow generation. It was found that even though the total runoff was significantly lower with jatropha plantations compared with the wasteland condition, base flow was in fact higher with jatropha plantations (Fig. 15.3c). On average, the total amount of base flow generation in the wasteland was only 70% of the base flow in the jatropha plantations. However, total runoff was 40% larger for the wasteland compared with the established jatropha.

Land management also affects runoff intensity. In general, higher runoff intensities were predicted for the wasteland state, compared with jatropha plantations (Fig. 15.3d). The results show that the average daily runoff intensity decreased by 12% for the current jatropha plantation, compared with the wasteland condition, and is likely to decrease even further with continued jatropha cropping (the established jatropha plantation had 39% lower runoff intensity than the wasteland).

A comparison of water balance components between the well-managed ICRISAT BL3 watershed and another site at the rural community of Velchal (current jatropha plantation) shows that a larger part of the rainfall formed green water flows (i.e. ET) at the well-managed site (80–90% compared with 40–60%, respectively) (Table 15.1). This means that only a small fraction (10–20%) of the total rainfall generated blue water flows (runoff and groundwater recharge) at the ICRISAT BL3 location. During dry years, blue water generation was lower than green water generation at both sites.

Sediment transport and soil loss

Currently, the estimated average soil loss in the Velchal watershed is between 10 and 15 t ha^{-1} $year^{-1}$. Because the soil depth is low and the available water holding capacity is poor in the watershed, large runoff is commonly generated during heavy rain with the capacity to carry large amounts of sediments. Soil loss was found to increase exponentially with rainfall intensity, and varied with land use (Fig. 15.4a). The highest soil loss occurred at high rainfall intensities under wasteland conditions. Cumulative soil loss generated at the watershed outlet over a 10 year period showed that jatropha cultivation resulted in a reduction of the total soil loss amount of nearly 50% compared to the wasteland state (Fig. 15.4b).

5.2.3 Jatropha plantations' impact on soil and environmental quality

Carbon and nutrient sequestration

Jatropha plants have a mechanism of drought avoidance by shedding their leaves during the stress period to minimize the water requirement,

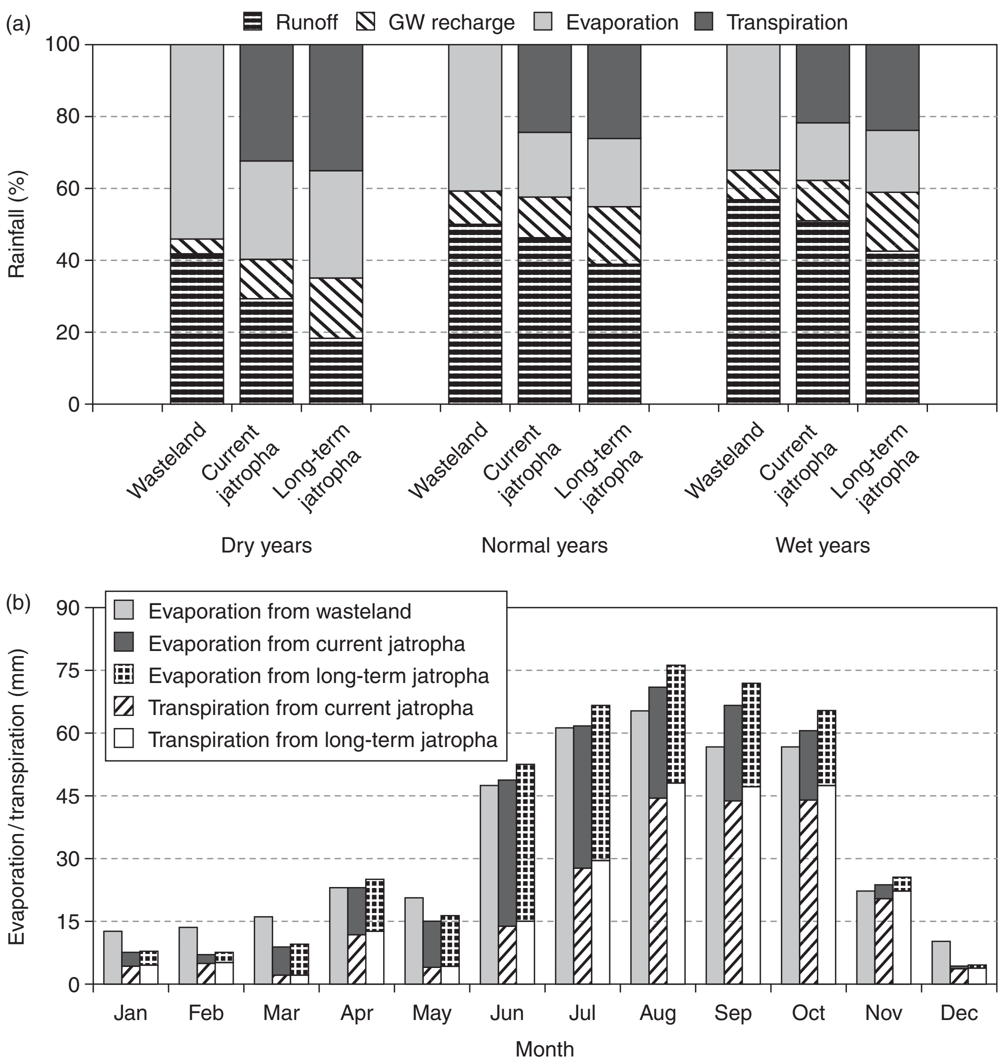


Fig. 15.3. (a) Water balance components of different land management scenarios during dry, normal and wet years (data from 2001 to 2010). (b) Monthly soil evaporation and transpiration for three different land management scenarios in Velchal watershed. (c) Total runoff generation from the watershed, divided into base flow and surface runoff, for three different land management scenarios during dry, normal and wet years (data from 2001 to 2010). (d) Frequency of daily runoff intensity for three different land management scenarios (data from 2001 to 2010).

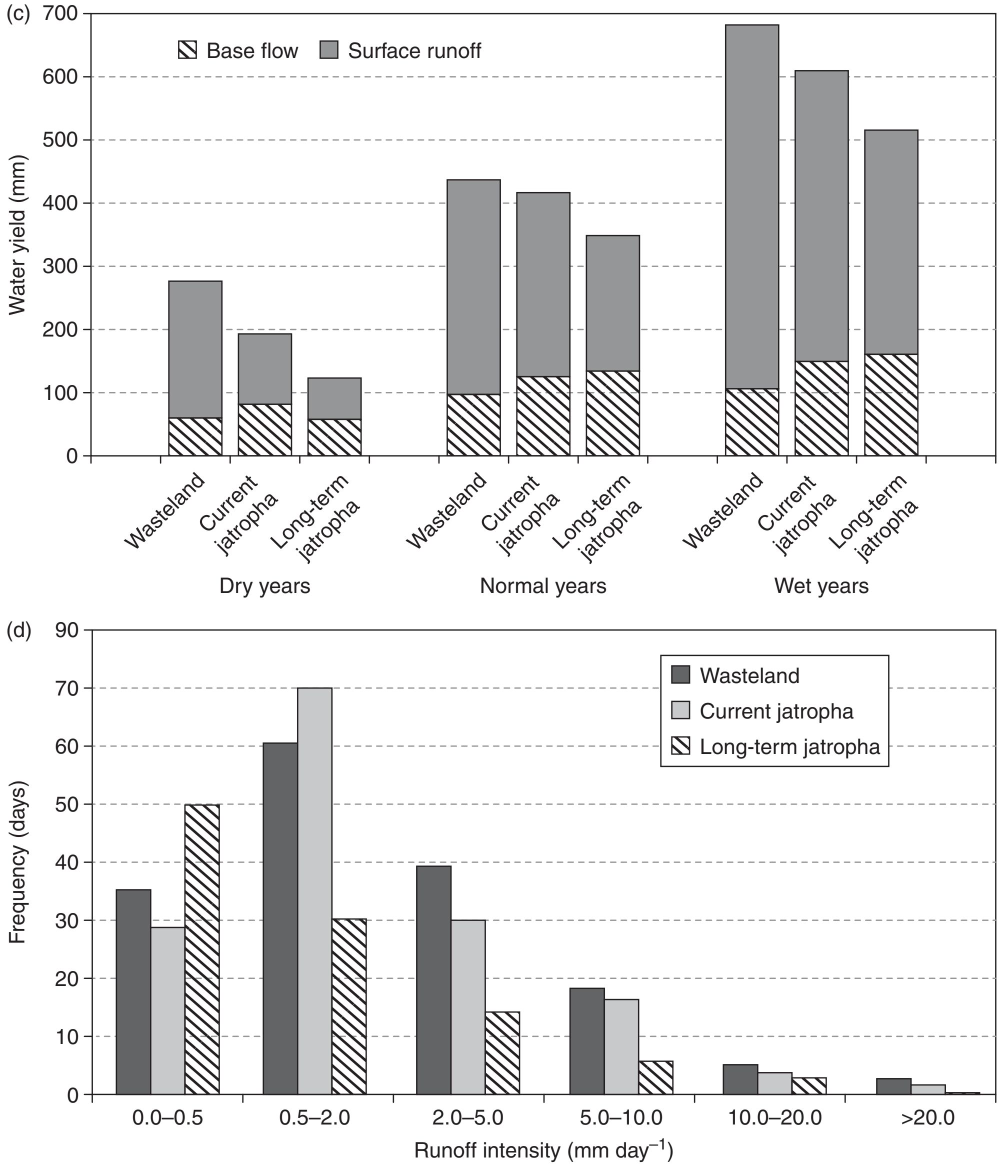


Fig. 15.3. Continued.

which is desirable in the rehabilitation of degraded lands through C addition to the soil. Data from the on-station study at two different ages of the plantation revealed an annual leaf fall of 552 g per plant in a 1-year-old plantation and 1451 g per plant in a 3-year-old plantation (Table 15.2), which corresponds to 305 kg C sequestrated ha^{-1} $year^{-1}$ through leaves in a 1-year-old plantation and 800 kg C sequestrated ha^{-1} $year^{-1}$ in a 3-year-old plantation comprising 1667 plants ha^{-1} at 2 × 3 m spacing. Jatropha pruned loppings generated around 410 kg ha^{-1} dry biomass and it was another source for adding C to the soil at the rate of 150 kg C ha^{-1}. The 3-year-old plants dropped around 2.6 times more leaves as compared to 1-year-old plants. The falling leaves in a 3-year-old plantation returned to the soil around 20 kg each of N and K and around 2 kg of P. Available P in the surface soil layer under jatropha was 5.2-fold

Table 15.1. Comparison of different hydrological components and crop yields between the ICRISAT BL3 watershed and the Velchal watershed ('current jatropha' scenario) (Garg *et al.*, 2011).

	Dry year (2007)		Wet year (2008)	
Variable (unit)	ICRISAT watershed, BL3	Velchal watershed	ICRISAT watershed, BL3	Velchal watershed
Inputs				
Available water (cm^3 cm^{-3}) (soil moisture at FC-PWP)	0.13	0.07	0.13	0.07
Soil depth (cm)	300	35	300	35
Annual average rainfall (mm)	707	707	1105	1105
Outputs				
Evaporation (mm)	251 (36%)	188 (27%)	265 (24%)	180 (16%)
Transpiration (mm)	400 (57%)	263 (37%)	606 (55%)	262 (24%)
Outflow (mm)	ND	162 (23%)	ND	550 (50%)
Groundwater recharge/deep percolation (mm)	ND	95 (13%)	ND	111 (10%)
Jatropha seed yield (t ha^{-1})	0.9	0.5	1.1	0.5

FC, field capacity; PWP, permanent wilting point; ND, not determined.

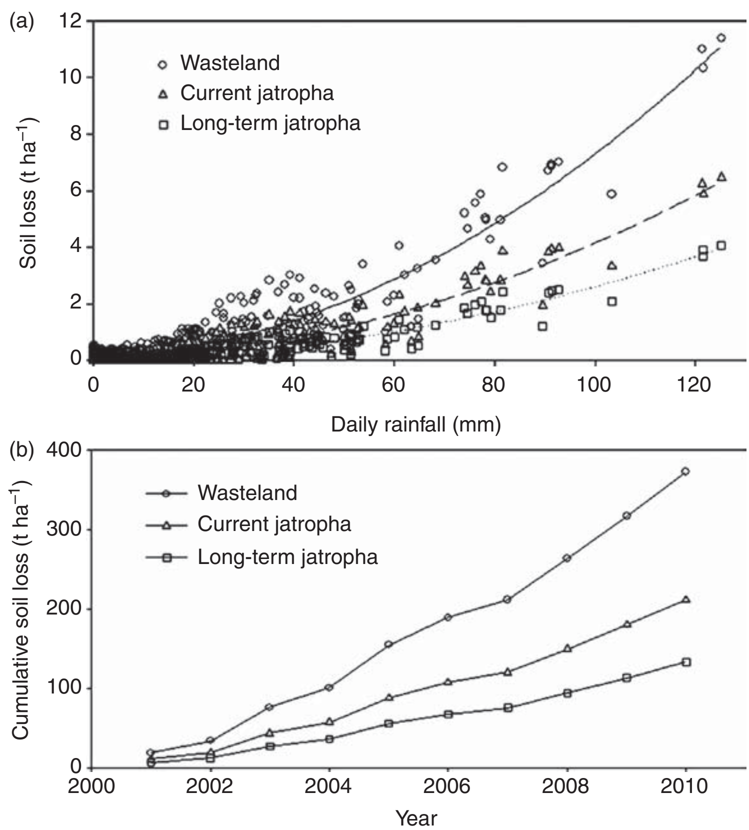


Fig. 15.4. (a) Impact of land management practices on sediment transport under different land management conditions (data from year 2001 to 2010). (b) Cumulative soil loss (t ha^{-1}) under different land management conditions (data from year 2001 to 2010).

as compared to the adjacent uncultivated control grasslands. A positive relationship was found between soil organic C and available P, implying the role of increased organic matter in enhancing soil P (Wani *et al*., 2003).

In the on-station study, the 4-year-old jatropha plantation recorded 1290 kg ha^{-1} seed yield in unfertilized control plots. The seed productivity varied from 1290 to 1610 kg ha^{-1} without and with fertilization and sequestered 580–725 kg C ha^{-1} year^{-1}. Out of the C sequestered in the seed, 185–230 kg C ha^{-1} year^{-1} is attributed to biodiesel/oil C replacement in the fossil fuel based on the amount of C in fossil fuel-based biodiesel equivalent to jatropha oil-produced biodiesel. After oil extraction, the by-product de-oiled seed cake is a good source of organic matter for improving soil health through organic carbon additions. The seed cake biomass returned 395–495 kg C ha^{-1} year^{-1} into the soil. This by-product is a good source of plant nutrients as well and has been evaluated for soybean and maize crops (Wani *et al*., 2006a; Osman *et al*., 2009).

The live plant (shoot and root) biomass standing in the fields is a good sink for C. The findings of the on-station study at Patancheru revealed that standing jatropha plants (4 years old) sequestrated 3.07 kg C per plant in above- and below-ground biomass, which corresponds to 5120 kg C ha^{-1} for a plant population of 1667 plants ha^{-1}. Similarly, the on-farm study at Kothlapur recorded 2.44 kg C-sequestration per plant, which translates to 6100 kg C ha^{-1} for a plant population of 2500 plants ha^{-1} at 2 × 2 m spacing.

Based on multiple study results, we have been able to conclude that a 3–5-year-old jatropha plantation in a tropical Indian location with 800 mm annual rainfall recycled around 4000 kg plant biomass or 1450 kg ha^{-1} equivalent organic C into the soil (Table 15.3). Further, biodiesel/oil extracted replaced 230 kg C ha^{-1} in the fossil fuel. In addition to the C in the recycled plant material and C replacement in fossil fuel, the live plantation also contained more than 5100 kg C equivalent ha^{-1} in biomass. In the tropics, identified agricultural C sequestering systems with the inclusion of pigeonpea and other legume and horticulture based cropping systems with improved management increased carbon sequestration by 330 kg C ha^{-1} year^{-1} (Wani *et al*., 2003; Bhattacharyya *et al*., 2007, 2009; Wani and

Table 15.2. Content and amounts of nutrients returned through fallen leaves during 2007 at ICRISAT, Patancheru (Wani *et al*., 2009).

Age of the plant (years)	Dry leaf (g/plant)	% N	% P	% K	Nutrient recycling by leaf litter (kg ha^{-1})		
					N	P	K
1	552.5	1.14	0.06	1.1	15.7	0.8	15.2
3	1451.1	0.86	0.08	0.95	20.8	2	23

Table 15.3. Total C sequestered through jatropha plantation as C returned to soil, biodiesel C replacement per year and live plant C.

C through jatropha plantation	Plant part involved	Organic C (kg ha^{-1})
C returned back to soil	Leaf fall	800[a]
	Pruned loppings	150[a]
	De-oiled cake	495[b]
C replacement in fossil fuel	Jatropha oil	230[b]
C in live plant	Shoots and roots	5120

[a]Leaf and stem prunings added C every year.

[b]Jatropha oil C (fuel replacement) and de-oiled cake added C from 4th year onwards every year.

Chaliganti, 2007). Addition of substantial amounts of C to degraded soil through jatropha would kick-start biological activity and nutrient release. Continuous addition of C to the soil would also bring an improvement in the water-holding capacity of the soil and would benefit the growing plants (Zhu *et al*., 2010). Such large quantities of C sequestrated in plant biomass is a great ecosystem service we can have and, as per the Kyoto protocol, these C credits can be traded with the countries or regions who are not able to manage their C credits (D'Silva *et al*., 2004).

Soil biology in the rhizosphere of Jatropha

Sustainability of plant–soil systems is largely governed by the floral and faunal biodiversity in the rhizosphere soils of the plant. Microbial biomass is an undifferentiated parameter of different microorganisms in soil, which play an important role in controlling nutrient cycling and availability to plants.

A study to evaluate the effect of jatropha plants on the soil biological activity at different locations and characterizing the difference between rhizosphere and non-rhizosphere soils of the plants was undertaken (Table 15.4). Soil samples (rhizosphere and non-rhizosphere) from four different locations (ICRISAT campus, Velchal, Siddhapur, Kothalapur) all in Andhra Pradesh, India, were studied for microbial counts, microbial biomass and dehydrogenase enzyme activity in the soil samples. The rhizosphere soil in locations planted with jatropha recorded high populations of bacteria, fungi and actinomycetes as well as dehydrogenase activity.

High microbial populations in rhizosphere soil indicates increased soil biological activity, which was also observed with increased microbial biomass C and N. The number of bacteria and actinomycetes in the rhizosphere soils of jatropha were more by 40 and 50%, respectively, than from the non-rhizosphere soil samples. Numbers of fungi in the rhizosphere soil samples were more by twofold than the non-rhizosphere soil samples. Although jatropha plants are non-edible for human beings as well as animals, microbes were not adversely affected but were stimulated due to rhizosphere effect of jatropha.

15.3 Cultivation

15.3.1 Field planting

Seedling multiplication and transplanting

Quality of the seedlings affects survival, growth and yield of the crop. Therefore raising healthy seedlings assumes importance. Jatropha seedlings can be grown by two methods, by the bare root and container method (polythene bag). In the bare-root method, a nursery bed is prepared by mixing farm yard manure (FYM), soil and sand in equal parts. Soaked seeds are sown at a row spacing of 25 cm and plant to plant spacing of 5 cm. The plants are ready for transplanting 6 weeks after germination; they are then carefully uprooted from nursery beds, wrapped in wet gunny bags and transplanted within 24 h. Before transplanting it should be ensured that enough moisture is available in the pit receiving bare-root seedlings.

Seedlings of jatropha can also be raised in poly-bags (10 cm × 18 cm, 150 gauge for 3–4-month-old seedlings) filled with 2 kg medium comprising equal parts of soil, sand and FYM. Diammonium phosphate (DAP) may be added at the rate of 1.0 g per poly-bag.

Table 15.4. Microbial population as influenced by jatropha plantation at Velchal, Andhra Pradesh, India (Susanna, 2009).

Microbial parameters	Non-jatropha plantation soil	Jatropha plantation soil	Coefficient of variation
Bacteria (cfu g^{-1} soil)	8×10^4	1×10^5*	54.6
Fungi (cfu g^{-1} soil)	1×10^3	2×10^3*	35.6
Actinomycetes (cfu g^{-1} soil)	8×10^2	8×10^2*	80.0

*Significant at 1%.

Good quality seeds having 80% germination should be sown at a rate of one seed per bag at 2–3 cm depth for getting higher percentage germination; 1 g of mycorrhizae (mixed culture) may be placed below the seed at the time of sowing to enhance growth of seedlings. In a study, jatropha seedlings treated with mycorrhizae had higher plant height, girth and number of leaves compared to control, when sampled 85 days after sowing. Grading and root pruning is suggested to promote uniform growth of seedlings.

The study on evaluation of the effects of propagation techniques in jatropha showed more than 80% survival rate in plots planted with poly-bag seedlings, followed by bare-root cuttings as observed 1 year after the planting. Planting of stem cuttings and direct sowing of seeds in the main field proved less effective and the survival rate was less than 20%.

Direct seeding

One to two seeds of jatropha (sprouted) per hole can be sown directly in the main field. The main field should be ploughed and spots receiving the seeds may be marked and enriched with FYM and DAP. Seedlings grown by this method will take time for establishment and will have slow growth in the initial period. However, the development of a good taproot provides strength to withstand wind damage. There should be enough moisture in the soil to support germination. Damage by birds and rodents to germinating seeds results in reduced plant stand. Frequent weeding is required to prevent the seedlings from competing weed and shade. Similarly soil working around the seedlings will boost growth and will improve the moisture and rainfall infiltration.

Vegetative propagation (transplanting of pre-rooted cuttings/grafting)

Jatropha can be multiplied by raising cuttings in a raised bed and later transplanting in the main field. Cuttings of 2–3 cm thickness from the lower portion of the shoot and having a length of 25–30 cm may be prepared in the March, when plants shed most of their leaves. These cuttings are planted in nursery beds at a spacing of 30 × 30 cm or in poly-bags. Pretreatment of stem cuttings with 300 ppm IBA (indole butyric acid) solution for 5 min is desirable. Sprouting starts within 7 days of planting. Plants propagated by cuttings will normally produce seed within 1 year of planting and growth is rapid. However, it has been observed that seedlings raised from seeds have better root systems compared to cuttings. The plants raised through cuttings will be true to type and will have similar characteristics of the mother plant but are prone to damage by strong winds as they lack proper taproots.

15.3.2 Fertilization

Though jatropha is well adapted to marginal lands, it responds to fertilizer application. Nutrient management is one such aspect, which may play a pivotal role in economic cultivation on marginal lands. Information available on nutrient requirements of jatropha is scarce and that on wastelands is non-existent. The work to evaluate the effect of nitrogen and phosphorus on growth and productivity of 4-year-old jatropha planted on wastelands at ICRISAT showed response to fertilizer application. In the on-station study, a 4-year-old jatropha plantation recorded 1290 kg ha^{-1} seed yield in the unfertilized control plots. The seed productivity varied from 1320 to 1610 kg ha^{-1} with nitrogen and phosphorus fertilizers applied. The highest productivity was recorded at 80 kg N and 20 kg P_2O_5 ha^{-1}.

Nutrients requirement for targeted jatropha seed yield based on nutrient budgeting

Detailed nutrient concentrations in different plant parts along with amount of plant materials returned to soil and seed removed from the fields for the purpose of oil extraction enables us to look at the nutrient requirements to achieve the targeted crop yields. Our results showed that 1 t jatropha seed removed 22 kg N, 5 kg P and 8 kg K ha^{-1}. The productivity level of 3 t seeds ha^{-1} will remove 66 kg N, 15 kg P and 24 kg K ha^{-1} year^{-1}. In order to sustain the productivity of the field at this level it is necessary to return equivalent quantities of N, P and K in simple arithmetic terms.

However, nutrient availability in soil from different sources of nutrients varied significantly depending on the C:N ratio, biological activity along with soil moisture and temperature. For mineral fertilizers, recovery of nutrients, for example, in the case of N is about 40–45%, whereas from organic matter of wider C:N ratio such as fallen leaves with 40:1 C:N ratio, N and other nutrient availability will be far less (<20%) during the first year of application. Leaf fall data and return of nutrients through leaf fall indicated that a 3-year-old plantation returned 21 kg N, 2 kg P and 23 kg K ha^{-1}. Applying the efficiency of release and uptake of N from the fallen leaf material it may be able to provide about 5 kg N ha^{-1} at best. It means that for achieving target yield of 3 t ha^{-1} seeds, one will need to meet the demand of additional 60 kg plant available N per ha and applying the basis of even 50% recovery from the chemical fertilizers one will need to apply about 120 kg N ha^{-1}. This will also be the case for phosphorus, which will need application of 14 kg P, i.e. 38 kg P_2O_5 ha^{-1}. These studies clearly indicate that sustainable jatropha production will definitely need application of plant nutrients in sufficient quantities. Leaf fall and application of oilseed cake after extraction of oil will only partially meet plant demand for nutrients such as N and P. Regular applications of other nutrients such as K, Zn, B and S may not be needed, as removal of these nutrients through seeds is low and return through leaf fall is considerable. However, detailed studies on nutrient release patterns from the fallen leaf material as well as oilseed cake are needed to arrive at the right nutrient dose applications to sustain seed yields.

15.3.3 Growth regulators

Jatropha is a monoecious shrub exhibiting protandry, where the flowers are unisexual, and male and female flowers are produced in the same inflorescence and male flowers open first followed by female flowers. Inflorescences produce a central female flower surrounded by a group of male flowers. Generally, there are 1–5 female flowers and 25–90 male flowers per inflorescence. The average male to female flower ratio is 29:1. As it is well documented in cucurbits that the use of growth regulators has the ability to manipulate sex expression, studies were conducted at ICRISAT during 2009 to evaluate the effect of growth regulators such as naphthalene acetic acid (NAA), gibberellic acid (GA), chlorocholine chloride (CCC) and ethrel on the male and flower ratio and yield of jatropha planted in the year 2004. The results revealed that yields were in general low due to unfavourable weather, but application of either CCC or GA at 90 and 25 ppm, respectively, at the time of flower initiation improved the flowering characteristics and crop yields (Table 15.5).

15.3.4 Pruning

Jatropha produces flowers in racemose inflorescences with dichasial cyme pattern in new growth branches, and hence the number of new branchlets determines the number of inflorescences. Therefore, pruning is essential to increase the number of fruiting branchlets, which is carried out by nipping the terminal bud to induce secondary and tertiary branches.

A study was carried out to assess the effects of pruning on canopy characteristics of jatropha in which half of the plants in the block plantation were pruned at 45 cm in the first year and 75 cm in the second year of growth during the dry season (February–March) when the plants are dormant, and the remaining half were grown without pruning. During the third year, the top one-third of the secondary and tertiary branches of plants were nipped off under the pruning treatment. The effect of pruning was observed on plant height, stem girth at 10 cm above the ground, number of branches, crown area, and volume index during the third year (Fig. 15.5). The results showed that pruning significantly ($p < 0.05$) influenced plant height (224 cm), stem girth (36 cm) and crown index (29) compared to the non-pruned plants, where the plant height, stem girth and crown index were 197 cm, 27 cm and 15, respectively. Similarly, the number of branches per plant was also more (43) in the pruned compared to the non-pruned (26) plants.

Table 15.5. Effects of application of plant growth regulators on jatropha productivity at ICRISAT, Patancheru, India during 2009 (ICRISAT, 2010).

Treatments	No. of inflorescences	Pod no.	Pod weight (g)	Seed no.	Seed weight (g)
Control	10.2	70.9	162.0	173.0	102.9
NAA at flower initiation (FI)	8.2	55.5	108.5	122.3	71.9
NAA at 1 month after FI	12.5	7.0	13.9	18.8	8.1
NAA at FI and 1 month after FI	9.8	6.3	18.3	19.0	10.2
GA at FI	10.0	158.0	384.5	400.8	247.5
GA at 1 month after FI	10.5	26.5	50.6	58.3	28.9
GA at FI and 1 month after FI	6.8	9.8	17.6	22.3	9.5
CCC at FI	9.8	152.0	366.6	415.5	249.2
CCC at 1 month after FI	10.7	12.3	27.3	30.5	16.2
CCC at FI and 1 month after FI	11.0	128.8	276.0	320.5	188.9
Ethrel at FI	10.3	35.5	107.9	120.2	71.3
Ethrel at 1 month after FI	7.2	94.0	207.6	219.8	134.1
Ethrel at FI and 1 month after FI	15.8	21.0	38.4	46.2	22.2

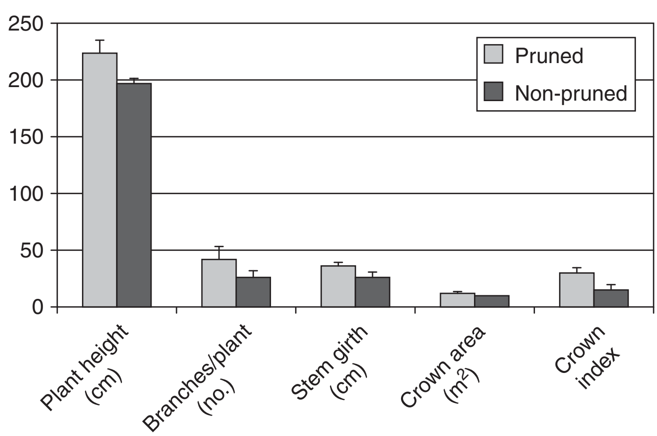


Fig. 15.5. Growth characteristics of jatropha plants due to summer pruning during the third year of establishment (Wani *et al*., 2009).

Jatropha is well adapted to drought conditions, but shows profuse growth under irrigated conditions compared to no irrigation. As the fruits are borne on new branches, the enhanced growth and number of branches has a direct relation to fruit/seed yield.

15.3.5 Insect pests and diseases

Jatropha has been believed to be less susceptible to insect pests and diseases merely based on a few observations from isolated plants. Insects such as leaf-eating beetles, thrips, leafhoppers, grasshoppers, caterpillars and leaf miner feed on foliage. Shoot/stem borer and bark-eating caterpillars damage the stem. Blue bugs and green stink bugs suck on fruits while capsule borer damages the fruits (Wani *et al*., 2006a). All the above pests may be controlled by spraying endosulfan at the rate of 3 ml l^{-1} water or any other pesticide recommended for that particular pest. Galls are formed due to the attack of mites and can be controlled by spraying dicofol at the rate of 5 ml l^{-1} water or wettable sulfur at the rate of 3 g l^{-1} water.

Diseases such as root rot, damping off, powdery mildew and leaf spots and cassava mosaic virus are frequently reported when the crop is raised as plantations (Wani *et al*., 2006b; Divakara *et al*., 2010). Black rot was observed during 2009 and 2010 in plantations in several Indian states including Andhra Pradesh, Assam, Chattisgarh and Madhya Pradesh (Srinivasa Rao *et al*., 2011). Affected plants (Fig. 15.6) showed drying along with shrivelling, discoloration of the stem with sticky reddish brown exudation at the base of plants. Black lesions on the stem under the bark and cambium layer were also observed. The symptoms spread to leaves and petioles as 1–3 mm diameter black spots and shrivelling and gummosis of hard wood, finally leading to death of the infected plant. The casual fungus was identified as *Botryosphaeria dothidea*. Spraying affected plants at the early stage of symptoms with bavistin (Carbendazim 50% WP) at the rate of 2 g l^{-1} controlled the spread of the symptoms and led to recovery of plants with new leaf growth after the rains (Fig. 15.7). Studies on regional incidences of insect pests and diseases are needed for development of an effective package of practices for economic cultivation.

15.3.6 Benefits through intercropping in jatropha during gestation period

Because jatropha takes a minimum 3–4 years before producing economic yields, intercrops provide additional income to the farmers during the gestation period. The feasibility of growing drought-tolerant field crops as intercrops with jatropha was studied on 3-year-old plantations on vertisols at the ICRISAT farm, Patancheru, India. Intercrops such as sorghum, pearl millet, pigeonpea, chickpea, sunflower, safflower, soybean and mung bean were successfully cultivated and evaluated in jatropha plantations during the rainy season and post-rainy seasons. Sorghum, pearl millet, soybean and chickpea yielded more than 1 t ha^{-1}. The intercrops' productivity in terms of grain yield varied from 0.29 t ha^{-1} in green gram to

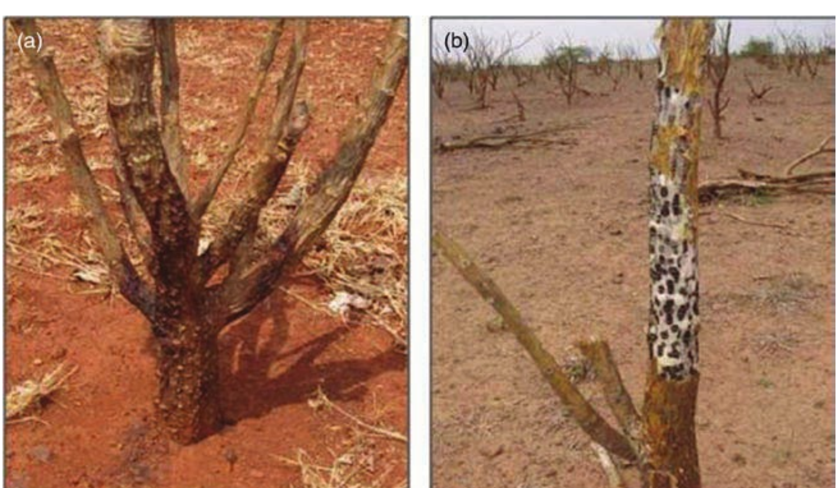


Fig. 15.6. *Jatropha curcas* plants infected with *Botryosphaeria dothidea*: (a) exudation of reddish brown gummy substance from the late infected stem and (b) black lesions over the stem under the bark.

Fig. 15.7. Initiation of new foliage from affected branches/ground after fungicide spraying in Velchal village plantation, Rangareddy district, during July 2009 (Srinivasa Rao *et al*., 2011).

1.5 t ha^{-1} in sorghum. Total economic value from additional income through grains and fodder from these crops varied from Indian Rs 5355 to Rs 20,430 per hectare.

15.3.7 Seed yield

Productivity of jatropha depends on precipitation rates, soil moisture availability, soil characteristics including fertility (Francis *et al*., 2005; Kumar and Sharma, 2008; da Schio, 2010; Jingura *et al*., 2011), genetics (Kaushik *et al*., 2007; Sunil *et al*., 2008; Divakara *et al*., 2010), plant age (Carels, 2009) and various management factors such as pruning, fertilization and disease control (Wani *et al*., 2006a; Kaushik *et al*., 2007; Achten *et al*., 2008; Behera *et al*., 2010; Ghosh *et al*., 2011; Jingura *et al*., 2011). Annual yield levels at 2–3 t dry seeds ha^{-1} have been proposed as achievable in semi-arid areas and on wastelands, while 5 t ha^{-1} can be obtained with good management on good soils receiving 900–1200 mm average annual rainfall (Foidl *et al*., 1996; Francis *et al*., 2005; Carels, 2009). Jongschaap *et al*. (2007) reported potential jatropha yields as high as 7.8 t dry seed ha^{-1} $year^{-1}$. The decorticated seeds yield about 28–40% oil (Wani *et al*., 2006a; Divakara *et al*., 2010), which can be transesterified and used for producing biodiesel (Jain and Sharma, 2010; Koh and Ghazi, 2011). Jatropha has not yet undergone breeding programmes with selection and improvement. The productivity varies greatly from plant to plant and environmental factors are reported to have a dominating role over genetics in determining seed size, weight and oil content (Kaushik *et al*., 2007).

15.4 Factors Controlling Up-scaling of Jatropha Cultivation

15.4.1 Farmers' interest in crop

Lack of interest shown by farmers to jatropha cultivation is one of the main problems to its large-scale adoption. The success of jatropha seed oil to be used for biodiesel production lies in the sustainable and economically viable production of seeds at the field level. Farmers do not yet consider jatropha cultivation sufficiently profitable due to the wrong perspective being adopted, i.e. it is considered as a cash crop grown on good soil, whereas in practice it is to be grown on lands that cannot be used for growing food or other commercial crops. Therefore, large-scale cultivation of jatropha has been put into question and concerns have been raised regarding its success. At the start, in a rush to push the crop, some of the plantings were set on productive lands. But when returns from oilseed yields from these plantings were compared to usual cash crops, jatropha fared poorly. This resulted in a poor first impression and caused a setback to the programme as well. Here, clarity has to be kept in mind that promotion of jatropha is for growing on lands unsuitable for agriculture and where hardy plants only can be grown, thus tapping unused land resources and bringing in additional benefit to farmers.

Among other issues challenging up-scaling are current low yields, lack of high-yielding cultivars, high harvesting costs, diseases and pests in block plantations, water balance changes and off-site impacts. Over and above all, the market for the seed is not secured and farmers are not very sure where to sell the seed. On the other hand, in the absence of seed-collection and oil-extraction infrastructure, it will be difficult to persuade entrepreneurs to install transesterification plants.

Farmers also are hesitant in view of: (i) lack of confidence due to the delay in notifying, publicizing and explaining the government biodiesel policy; (ii) in the absence of long-term purchase contracts, there are no buy-back arrangements or purchase centres for jatropha; (iii) lack of availability of certified seeds with higher yield and oil content; and (iv) no announcement of incentives and other benefits to farmers. The government needs to take confidence-building measures and address farmers' concerns. Financial assistance should be given to organizations in developing a large-scale awareness/training programme for farmers.

15.4.2 Coherent national policy on biofuels

A country-wide policy to facilitate production of feedstock and processing is essential to bring the jatropha biodiesel programme to fruition. State by state policy differences create confusion and limited progress. In India, a petrol blending programme mandated 5% ethanol blending of petrol, initially for selected states and union territories and in 2006 extended to the whole country (Ministry of Petroleum & Natural Gas, 2008). Realizing the urgency, the Government of India (2009) has formulated and approved a National Policy on Biofuel along with setting up an empowered National Biofuel Coordination Committee, headed by the Prime Minister and a Biofuel Steering Committee headed by a Cabinet Secretary. Under the approved policy, the country aims to increase blending of biofuels with gasoline and diesel to 20% by the year 2017 (Achten *et al*., 2010b). The policy focuses on indigenous production of biodiesel in waste/degraded/marginal lands. It incorporates the announcements on Minimum Support Price (MSP), with the provision of periodic revision for biodiesel oilseeds to provide a fair price to the growers, which would be based on the actual cost of production. In the case of biodiesel, the MSP could be linked to the prevailing retail diesel price. The National Biofuel Policy envisages that biofuels, namely, biodiesel and bioethanol, may be brought under the ambit of 'Declared Goods' by the Government to ensure unrestricted movement of biofuels within and outside the states. It is also stated in the policy that no taxes and duties would be levied on biodiesel.

15.4.3 Availability of sufficient degraded land for planting

Historically, while studying the bioenergy potential the availability of suitable land is the primary concern and focus. The recent Government of India assessments have identified 16% of the geographical area (>350 Mha) as wasteland (GOI, 2010). Keeping in mind the 400 million poor in India, and the fact that

70% of the poor in India are small/marginal farmers and landless labourers (GOI, 2010), it is essential that wasteland development programmes are undertaken to generate the needed socio-economic benefits for poor farmers and labourers.

The National Mission on Biofuels in India has identified about 13.4 Mha for jatropha (and pongamia) plantations in the immediate future and it covers poor, marginal, degraded, fallow, waste and other lands such as along the canals, roads, railway tracks, on farm and property bunds in the arid and semi-arid areas. Once success is achieved on potential lands, it should be possible to include lands with low fertility soils, which can be brought under jatropha plantation in an economically feasible manner to rehabilitate them. By adopting knowledge-based and pro-poor strategy, non-edible oils can be used for biodiesel production. Pro-poor biopower strategy leads to a win-win-win situation – improve livelihoods, protect the environment and have energy from renewable sources (ICRISAT, 2007). Other developing countries also have land area unfit for crop production and jatropha production may provide a suitable option.

15.4.4 Employment generation and social mainstreaming

The biofuels sector has the potential to successfully rehabilitate degraded lands and so improve the livelihoods of the rural people by providing employment and additional sources of income (Wani *et al*., 2006a). Biofuel plantation activity on a commercial scale provides employment at village level through plantation, agronomic management, seed collection and through markets for fertilizer, pesticides, fuel and industrial raw materials for soap/cosmetics, etc. Developing nations are looking towards biofuels to help reduce their spiralling foreign oil import costs, and to mitigate pollution and global warming. The carbon credits gained through the fuel switch can also be a source of income to the rural people as these can be traded with the other developing or developed regions/countries.

A large part of the population in developing countries, mostly in rural areas, does not have access to energy services. There is an increasing gap between supply and demand, in addition to a continuous deterioration in quality of power and a low level of access to electricity. Lack of access to affordable energy services among the rural poor seriously affects their chances of benefiting from economic development and improved living standards. Under such circumstances decentralized power generation using biofuels is the need of the hour. Access to modern decentralized small-scale energy technologies, particularly renewable biofuels, is an important element for effective poverty-alleviation policies. A programme that develops energy from raw material grown in rural areas will go a long way in providing energy security to the rural people for their domestic use, farm production activities (e.g. irrigation, etc.) and engagement in livelihood activities (e.g. small processing mills), leading to improved incomes, better living and their social mainstreaming.

Another advantage of jatropha cultivation is that the former use of land for grazing can be continued. This means that nobody in the village will lose their customary right due to jatropha plantations. Grazing in jatropha plantations may raise concerns about the potential intoxication of livestock. Toxicity in jatropha is due to the presence of toxalbumin of nomecurcin (toxin protein), which irritates the gastrointestinal mucosa and also haemoagglutinates and causes nausea, vomiting, intense abdominal pain and diarrhoea with bloody stools (Ribeiro and Matavel, 2009). However, such incidence in a study village has not been reported, probably because animals quickly perceive the danger of consuming jatropha.

An additional benefit to the community from jatropha cultivation is higher groundwater tables, which improves access to water for domestic and agricultural use. Achten *et al*. (2010a) thoroughly discussed the benefits of jatropha cultivation in wastelands at a local scale. After oil extraction, seed cake could not be used for animal feed due to its toxic content but it could potentially be used as fertilizer and biopesticide/insecticide and molluscicide simultaneously (Rug *et al*., 1997). Moreover seed cake could be used for biogas production through anaerobic digestion before using it as a soil amendment (Staubmann *et al*., 1997).

The calculations show that the 3–5 years that it takes to cultivate 1 ha of jatropha has production costs between US$740 and US$920. As jatropha has such a long period without any financial return, there must be provisions to ensure the economic stability of the farmers. Flexible and long-term financing options could facilitate the expansion of agrofuel production. The assumed bank loan covering the initial expenditures could be broadened, providing different financing options for farmers, as well as increasing overall access to financial support and reducing the interest rate for repayment.

15.5 Genetic Improvement of Jatropha

Very little is known about the jatropha genome and not many systematic efforts for improvement of this crop have been undertaken. Improved varieties with desirable traits for specific growing conditions are not available, which makes growing jatropha a risky business (Wani *et al*., 2006a; Jongschaap *et al*., 2007). Chromosomes are of very small size (bivalent length 1–3.67 μm) with most species having $2n = 22$ and base number of $x = 11$ (Soontornchainaksaeng and Jenjittikul, 2003). It is an attractive candidate for genome sequencing with genome size (1C) of 416 Mbp (Carvalho *et al*., 2008). Because jatropha is an introduced plant to many countries of Asia, Africa and Latin America, genetic variability has not been much explored for genetic improvement.

Genetic improvement of jatropha is suggested through mutation techniques. Selection of germplasm and identification of pistillate variants (Hegde, 2003) as followed for castor (*Ricinus communis* L.) belonging to the same family is also recommended (Sujatha, 2006; Sujatha *et al*., 2008). Development of pistillate plants through mutation and interspecific hybridization techniques is time consuming. Alien gene transfer through interspecific hybridization and biotechnological interventions to bring the change in the desired traits and/or to identify divergent parents, which can later be exploited by heterosis, is also suggested. Meanwhile, physiological manipulation of sexuality, applying gametocides to enhance the M/F ratio and altering the expression levels of enzymes in the triacylglycerol-biosynthetic (Kennedy) pathway (King *et al*., 2009) may also be considered to increase yield.

The objective for genetic up-gradation of the crop should aim at a higher number of female flowers or pistillate plants, high seed yield with high oil content, early maturity, resistance to pests and diseases, drought tolerance/resistance, reduced plant height and high natural ramification of branches. Jatropha is often a cross-pollinated crop and can be improved through mass selection, recurrent selection, mutation breeding, heterosis breeding and interspecific hybridization or biotechnological interventions to bring the change in the desired traits (Divakara *et al*., 2010).

15.5.1 Tapping germplasm for potential productivity

Genetic diversity in plant species is a gift to mankind as it forms the basis for selection and further improvement for increasing the yield potential as well as other desired traits. However, comprehensive work on a jatropha germplasm collection, characterization and evaluation for growth, morphology, seed characteristics and yield traits is still in its infancy. The fact that jatropha has adapted itself to a wide range of edaphic and ecological conditions suggests the existence of a considerable amount of genetic variability to be exploited for potential realization (Rao *et al*., 2008). Detailed and systematic provenance trials have not been carried out, and material from the centre of origin has not been sufficiently screened. The genetic background of jatropha grown in Africa and Asia is unclear and G × E interaction amongst the provenances needs to be taken into account while considering the reported variations (Namkoong *et al*., 1988). Priority should be given to assess intra- and inter-accessional variability in the available germplasm, selection of pure lines and then multiplication.

Existence of natural hybrid complexes is reported in the genus *Jatropha*, such as the *J. curcas–canascens* complex in Mexico (Dehgan and Webster, 1978), *J. integerrima–hastata* complex in Cuba and West Indian islands (Pax, 1910) and *J. curcas–gossypifolia* (*J. tanjorensis*) in India (Prabakaran and Sujatha, 1999). Hence, germplasm exhibiting gross morphological differences should be the subject of pollen studies and lines with pollen abnormality or poor seed set should be investigated in detail before drawing conclusions about the distinctness (Divakara *et al*., 2010). Makkar *et al*. (1997) reported large variations in contents of crude protein, crude fat, neutral detergent fibre and ash on 18 different provenances of jatropha from countries in West and East Africa, the Americas and Asia. Wani *et al*. (2006a) recorded variation in Indian accessions for oil content (27.8–38.4%) and 100-seed weight (44–77 g). Kaushik *et al*. (2007) explored the variability in Haryana, India accessions to find wide variation in 100-seed weight (49–69 g) and oil content (28–39%). Similarly, Rao *et al*. (2008) found wide variation in 100-seed weight (57–79 g) and oil content (30–37%) for Andhra Pradesh, India, accessions.The study conducted at ICRISAT on progeny trial evaluation comprising 99 jatropha accessions collected from different agro-eco regions of India and planted during 2006 showed great variability in plant height (105–274 cm), collar diameter (5.1–18.9 cm), number of branches (9.7–66.3), crown area (0.5–6.3 m^2), volume index (8056–85,708 cm^3), seed length (11.6–19.3 mm), seed width (9.5–11.7 mm), seed thickness (7.6–11.0 mm), 100-seed weight (38.9–67.1 g) and seed oil content (27.5–40.5) (Table 15.6). ICJC06116 recorded the highest 100-seed weight of 67.1 g. Genotype ICJC06004 recorded the highest plant height (274 cm) and ICJC06087 the highest volume index (85,708 cm^3) and collar diameter (18.9 cm). The number of branches and crown area were highest in ICJC06115 (66.3) and ICJC06010 (6.3 m^2), respectively. Highest seed length was seen in genotype ICJC06082 (19.3 cm) while genotype ICJC06055 showed the maximum seed width (11.7 cm) and thickness (11.0 cm). Highest oil content for seeds was 40.5% in genotype ICJC06019. As a whole, 44% of the genotypes have exhibited seed oil content in the range of 35.1–40%.

In India, the National Oilseeds and Vegetable Oils Development (NOVOD) Board (Ministry of Agriculture, Government of India) has identified 1855 candidate plus trees (CPTs) of jatropha and has over 5000 accessions

Table 15.6. Performance of selected *Jatropha curcas* genotypes for growth and seed traits at ICRISAT during 2008 (planted 2006) (ICRISAT, 2010).

Genotypes	Plant height (cm)	Collar diameter (cm)	Number of branches	Crown area (m^2)	Volume index (cm^3)	Seed length (mm)	Seed breadth (mm)	Seed thickness (mm)	100-seed weight (g)	Oil content (%)
ICJC06004	274	16.0	52.1	5.3	76,077	17.9	10.9	9.1	53.9	31.2
ICJC06010	226	15.0	54.5	6.3	51,563	17.9	10.9	8.6	51.2	37.8
ICJC06019	228	12.8	41.4	2.4	38,653	16.6	11.4	10.7	52.3	40.5
ICJC06055	135.9	5.8	14.9	0.8	8,972.8	16.7	11.7	11.0	46.1	34.9
ICJC06066	168	6.4	23.4	0.8	10,433	16.9	10.6	7.6	54.8	32.1
ICJC06082	207.5	14.0	32.4	1.5	41,756.3	19.3	10.3	9.3	53.3	35.0
ICJC06087	233.2	18.9	51.5	3.5	85,708	18.2	11.3	9.0	56.8	37.3
ICJC06091	202	18.3	51.0	3.4	68,345	17.6	11.5	10.3	64.3	39.1
ICJC06115	213	14.7	66.3	3.2	48,761	17.3	11.4	10.7	66.7	34.8
ICJC06116	205	17.6	61.9	3.5	64,976	19.1	11.5	8.9	67.1	29.4
ICJC06117	201	15.3	62.2	3.7	50,474	17.7	11.6	10.8	58.2	34.7
ICJC06120	198	10.6	48.5	2.3	23,850	18.7	11.0	8.6	66.6	34.4
Mean (of 99)	204	11.8	37.3	2.0	33,935	17.4	11.1	9.1	52.7	34.7
SEM	14.1	1.3	5.8	0.5	8,288.9	0.2	0.2	0.1	3.4	0.3
CD (5%)	43.6	3.9	17.8	1.3	25,664	0.6	0.5	0.4	11.2	0.8

collected with a network of 40 institutions. The oil content varies from 26.0% to 42.7% (Punia, 2007). Department of Biotechnology (DBT), Government of India, launched a micro-mission on the production of quality planting material with 30–40% oil and 3–5 t ha^{-1} seed yield; under this mission, 1500 accessions have been collected (Swarup, 2006). Kaushik *et al*. (2007) analysed 1000 samples of jatropha seeds representing 12 states of India for oil content and kernel seed-coat ratio and reported that a collection from Uttaranchal recorded the highest percentage of high-oil-yielding plants (73%). Most of the jatropha varieties spread worldwide (e.g. the variety 'Cape Verde', a variety from Nicaragua and a non-toxic variety from Mexico) were developed from good performing selections from the existing natural population and were not the result of targeted crossings (Heller, 1996). The first variety, 'SDAUJ I' ('Chatrapati'), has been identified for commercial cultivation in the semi-arid and arid regions of Gujarat and Rajasthan in India (http://www.icar.org.in/pr/10052006.htm). The Indian Council of Agricultural Research (ICAR) launched a network project in which 28 seed sources were identified as the best among 496 seed sources (Paramathma *et al*., 2009).

15.5.2 Assessment of variability in jatropha accessions using molecular markers

Microsatellite markers are available for a few *Euphorbiaceae* members and are being developed for castor (Lespinasse *et al*., 2000; Okogbenin *et al*., 2006; http://castorbean.tigr.org). As the developmental costs for microsatellite markers are high, cross-taxa utility of molecular markers from *Hevea* and cassava could be assessed as done in other plant species (Rossetto, 2001). Divakara *et al*. (2010) reported that the majority of the studies are confined to characterization of accessions available in India; the exceptions are Basha and Sujatha (2007) with one non-toxic accession from Mexico, Montes *et al*. (2008) with accessions from 30 countries and Sun *et al*. (2008) with accessions from south China (Table 15.7). Regardless of the number of accessions used, the robustness of the primer and number of marker data points, all accessions from India clustered together. In general, diversity analysis with local germplasm revealed a narrow genetic base in India (Basha and Sujatha, 2007; Ganesh Ram *et al*., 2008) and south China (Sun *et al*., 2008), indicating the need for widening the genetic base of jatropha through introduction of accessions with broader geographical background and creation of variation through mutation and hybridization techniques. In contrary to the above studies, AFLP (amplified fragment length polymorphism)-based molecular characterization of jatropha accessions from Andhra Pradesh were found to be diverse as these were scattered in different groups, showed the occurrence of a higher number of unique/rare fragments and had greater variation in percentage oil content (Tatikonda *et al*., 2009). Forty-eight accessions, collected from six different states of India, were used with seven AFLP primer combinations that generated a total of 770 fragments with an average of 110 fragments per primer combination. A total of 680 (88%) fragments showed polymorphism in the germplasm analysed, of which 59 (8.7%) fragments were unique (accession specific) and 108 (15.9%) fragments were rare (present in less than 10% accessions). In order

Table 15.7. Characterization of accessions using molecular markers (Divakara *et al*., 2010).

Species/ accessions	Primers	Number	References
142	AFLP	–	DBTIndia, 2007
5	RAPD	18	Ganesh Ram *et al*., 2008
22	RAPD DAMD	7 4	Ranade *et al*., 2008
13	RAPD ISSR	20 14	Gupta *et al*., 2008
7	RAPD AFLP	52 27	Pamidimarri *et al*., 2008
20	RAPD AFLP	– –	Reddy *et al*., 2007
43	RAPD ISSR	400 100	Basha and Sujatha, 2007
225	AFLP	–	Montes *et al*., 2008
58	SSR AFLP	30 7	Sun *et al*., 2008

to assess the discriminatory power of the seven primer combinations used, a variety of marker attributes such as polymorphism information content (PIC), marker index (MI) and resolving power (RP) values were calculated. Although the PIC values ranged from 0.20 (E-ACA/M-CAA) to 0.34 (E-ACT/M-CTT) with an average of 0.26 per primer combination and the MI values were observed in the range of 17.60 (E-ACA/M-CAA) to 32.30 (E-ACT/MCTT) with an average of 25.13 per primer combination, the RP was recognized as the real attribute for AFLP to determine the discriminatory power of the primer combination. The RP values for different primer combinations varied from 23.11 (E-ACA/M-CAA) to 46.82 (E-ACT/M-CTT) with an average of 35.21.

However, careful understanding of the phylogeny and use of an adequate number of molecular markers are essential prerequisites for drawing valid inferences about the genetic affinities (Sujatha *et al*., 2008). Basha and Sujatha (2009) characterized jatropha species occurring in India using nuclear and organelle-specific primers, which revealed high interspecific genetic variation (98.5% polymorphism). Further characterization of both natural and artificially produced hybrids using chloroplast-specific markers revealed maternal inheritance of the markers (Basha and Sujatha, 2009). In support, genetic variation studies using RAPD (random amplified polymorphism DNA), AFLP and combinatorial tubulin-based polymorphism (cTBP) indicated higher possibilities of improving *J. curcas* by interspecific breeding (http://precedings.nature.com/documents/2782/version/1). Hence, molecular diversity estimates combined with the datasets on other agronomic traits will be very useful for selecting the appropriate accessions.

15.5.3 Jatropha genome project

The jatropha genome is approximately 400 million bp in size, similar to the size of the rice genome based on the sequencing of the genome, using both traditional Sanger sequencing and next-generation sequencing. Work in progress on the annotation of the genome to identify genes of interest helps in discovering genetic variations using marker-assisted breeding and provides information on factors controlling oil synthesis, maximizing yield, biotic and abiotic stress tolerance and low-curcin variants (http://greenbio.checkbiotech.org/news/first_Jatropha_genome_completed_synthetic_genomics_inc_and_asiati 511 c_centre_genome_tech).

Divakara *et al*. (2010) indicated that *J. curcas* is still in its infancy with respect to genetic improvement for increasing seed and oil yield per unit area. Genetic improvement activities so far have involved only collection and selection in local germplasm and hence initiatives to evaluate global germplasm is necessary, to study the pattern of diversity for various traits. Genetic improvement using conventional breeding approaches has to be initiated at more places and integrated with the latest biotechnological techniques for reducing time and increasing efficiency of breeding. Potential of the new varieties developed has to be further tested for their performance, through multilocation trials. Development of techniques, such as somoclonal variants, mutations, doubled haploids and gene transfer, that support plant-breeding activities should be emphasized. Similar to other crops, heritability of seed traits is the most common predictor of genetic gains for different breeding methods in jatropha. Application of information from the jatropha genome project can be used in marker-assisted breeding to accelerate and complement conventional breeding.

15.4 Jatropha Products

Biodiesel was probably the first of the alternative liquid fuels to become known to the public. The advantage in biodiesel is that it can be used in existing vehicles with little or no modification required when used as blended. During the last few decades researchers tried many edible and non-edible oils in compression ignition for different utilities. There are energy plants available that will produce a higher yield in kWh per area, but the simplicity of having a fuel that is fully compatible with present fuel and engine technology makes jatropha biodiesel very attractive. Jatropha biodiesel has good fuel properties, comparable to or even better than petroleum diesel (Rao *et al*., 2008). The cetane number (an indication of its fuel-burning efficiency) is 51–52 for biodiesel from jatropha oil, which is higher than the cetane number of most petroleum diesels. It has 10% built-in oxygen content that helps it to burn fully. The esters of the long-chain fatty acids of biodiesel are excellent lubricants for the fuel injection system. It has a higher flash point than diesel, making it a safer fuel. But there are a few technical issues that need to be resolved. Biodiesel has a high viscosity at low temperatures, leading to flow problems at these temperatures.

Straight vegetable oils from jatropha are also used directly in high rpm diesel engines for power generation as well as pumping water (D'Silva *et al*., 2004). The use of blended fossil fuels with biofuels results in reduction of unburnt hydrocarbons by about 30%, carbon monoxide by about 20% and particulate matter by about 25%. Moreover, sulfur content in the emissions from the use of blended fuels is almost negligible (Francis *et al*., 2005). ICRISAT (2008) has assessed the performance of the vehicles (eight TATA Mobile 207Di, two Nissan Diesel and one Toyota Qualis) since May 2007 run on blended fuel at 10% biodiesel. The detailed examination of the engines by automobile engineers at ICRISAT indicated no abnormal wear or tear of the engine as well as any changes in the kilometreage with the blended fuel. No starting trouble or pick-up problem was observed in any vehicle. There was no abnormal smoke or other specific complaints from the users while driving the vehicle.

Jatropha oilcake contains all the macro- and micronutrients and it is an excellent organic fertilizer unlike inorganic fertilizers that supply one or two nutrients. A mass of 4 kg of jatropha seed gives about 3 kg of cake, which is generally sold at Indian Rs. 3 to 7 per kilogram depending upon the demand and supply scenario. The cake is mostly used for fertilizing plantation or commercial crops. An analysis of jatropha cake indicated the presence of all the essential elements required for plant growth, and was particularly found to be rich in nitrogen and sulfur.

Similar studies carried out in Zimbabwe have revealed that application of jatropha cake at the rate of 0, 0.25, 0.5 and 1.0 kg m^{-2} resulted in cabbage yield of 16.8, 23.6, 22.8 and 35.8 kg, respectively, and the crop was free from pests and diseases. Tasosa *et al*. (2001) have recorded a significant difference in growth rates of tomato and total above-ground dry matter with increased application rates of jatropha and castor cakes. Henning (2009) is of the opinion that jatropha plants can reduce the soil and water erosion when planted as a living fence and the cake obtained after oil extraction can help in building the organic matter content of the soils of Sahelian countries. Substitution of fertilizers with oilseed cake is likely to improve the fertility of the soils in the long run and the soils will overcome the widely observed deficiency of several nutrients such as N, P, Z, B, S, etc. Further, it will reduce the dependence of farmers on external input (fertilizers). Recycling of the cake serves the interest of farmers as well as government as the huge subsidy paid on fertilizers to industries in most countries can be reduced. The amount saved on subsidy of fertilizers can be used for encouraging biodiesel plantations in rural areas for ensuring energy, food and livelihood security (Osman *et al*., 2009).

The biodiesel processing produces glycerol of about 88% purity, which is about 12% in volume to the biodiesel produced. At present there is limited market for glycerol but research efforts are underway to find alternative uses.

15.4 Economic Assessment

The key determinant of the financial analysis to estimate the economic viability of jatropha production is the calculation of the net present value (NPV; difference between the present value of cash inflows and the present value of cash outflows). The investment in jatropha seed production is judged as economically viable when the NPV is above zero. Different interest rates (6–16%) are used to simulate investment alternatives, which are also applied to the NPV calculations. The results showed that for the low-cost scenario, the production of jatropha seed to be used for JPPO (jatropha pure plant oil) becomes economically viable at rates above a crude-oil price of US$75 per barrel (interest rate 6%). For JME (methylated ester) the NPV (interest rate 6%) for jatropha seed production first becomes positive at crude-oil prices above US$90 per barrel. At an interest rate of 16% and under the low cost assumptions, the use of jatropha seeds for JPPO needs a crude oil price greater than US$105 per barrel and JME needs a crude oil price above US$120 per barrel. For the average cost scenario, jatropha seed production becomes economically viable for JPPO at crude-oil prices above US$100 (interest rate 6%) whereas JME requires crude-oil prices of at least US$115 (interest rate 6%). The economic viability of jatropha seed production under wasteland conditions can differ considerably depending on the applied interest rate and production costs. As shown in Figs 15.8 and 15.9 even at a crude-oil price of US$150 per barrel the high-cost scenario reaches no positive NPV for both jatropha fuel options.

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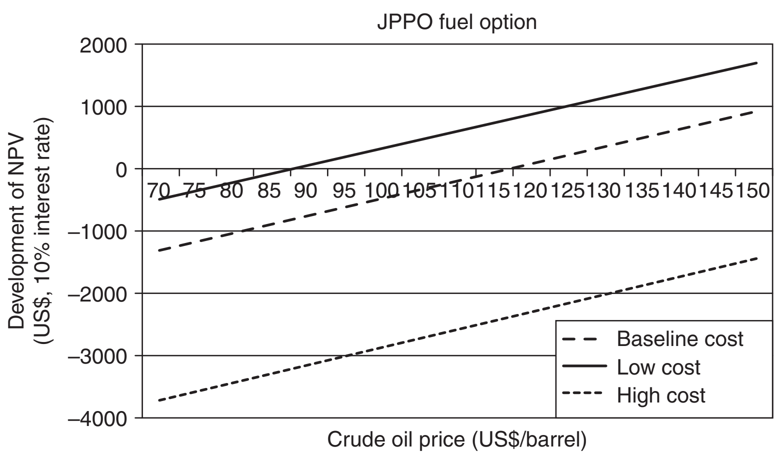

Fig. 15.8. Development of NPV for jatropha seed production according to the JPPO (Jatropha Pure Plant Oil) fuel option and different crude-oil price levels (Grass, 2010).

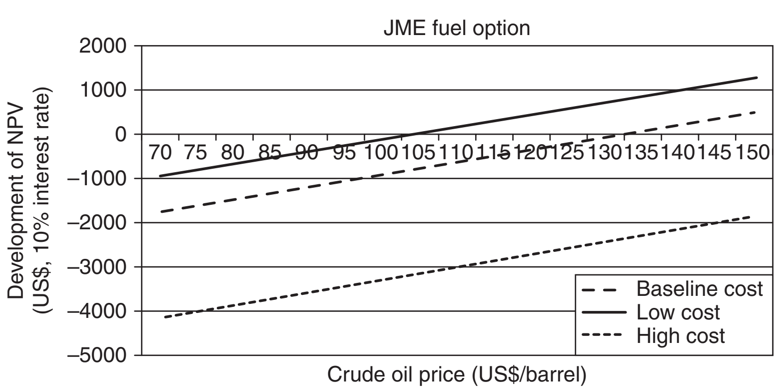

Fig. 15.9. Development of NPV for jatropha seed production according to the JME (Jatropha Methyl Ester) fuel option and different crude-oil price levels (Grass, 2010).

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