

Chapter

Evaluation Trials and Carbon Sequestration Potential of *Jatropha curcas* and *Pongamia pinnata*: Technologies and Way Forward

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Abstract

The Chapter focuses on two crops namely *Pongamia pinnata* and *Jatropha curcas*, their germplasm collection, evaluation trials including progeny trials, identification of superior germplasm for maximum yield of oil per unit area, mass multiplication, on-farm trials, carbon sequestration capacity, and successful agro-forestry models. Since India's edible oil consumption needs are heavily dependent on imports, the only feasible way to augment biofuel production is through utilisation of non-edible tree borne oils. Indian demography (population size and population density) coupled with food-fuel competition warrants the use of only wastelands for cultivation with crops tolerant/resilient to severe environmental stress. *P. pinnata* and *J. curcas* are proven, ideal candidates that fit in the narrative and hence the chapter encompasses a holistic, multi-dimensional approach on biodiesel production technologies using *P. pinnata* and *J. curcas* and along with their future prospects.

Keywords: biodiesel, production technologies, tree-borne oilseeds (TBOs), agroforestry, carbon sequestration potential

1. Introduction

Global warming and climate change has shifted the energy requirement paradigm from fossil fuels to biofuels. Among the different biofuels production technologies, Tree Borne Oilseeds (TBOs) provide a unique production substrate as it possesses 15–65% oil content from seeds of multi-purpose tree species, which are non-edible and can be utilised as a source of bio-diesel production. Moreover, TBOs has enormous potential in ensuring livelihood security because it involves participation of communities in growing trees as a component and processing of seeds for oil extraction. These oil tree species can be grown across the country under different agro-ecological regions ranging from forests, non-forest areas, degraded lands, barren lands, deserts and hilly landscapes.

Although biofuels derived from TBOs have proven to be ideal eco-friendly candidates for energy security, its mass production remains arduous due to several

technological and economic issues ranging from commercial production and harvesting of TBOs at optimum maturity index. The prime impediments in establishment of an integrated system of large-scale TBOs production are the non-availability of a robust marketing chain with horizontal and vertical linkages and lack of government aided monetary incentives.

India has an appreciable repository of non-edible tree borne oilseeds as well as the required policies that render them amenable to increased biofuels production. There is also a large collection of germplasm accessions for important TBOs such as *Jatropha curcas*, *Azadirachta indica*, *Pongamia pinnata* and *Madhuca longifolia* that are being maintained and evaluated at different research facilities in the country. In the Research and Development (R&D) front, there have been substantial advancements in aspects such as genetic variability at morphological, biochemical and molecular level, diversity, growth pattern, reproductive biology, yield, propagation, crop improvement, carbon sequestration potential and agroforestry opportunities. What remains to be addressed are the problems encountered in TBOs such as seed collection from scattered locations, processing, high dormancy and problems in picking and harvesting in avenue and forest plantations, non-availability of quality planting material or seed, limited period of availability, unreliable and improper marketing channels, lack of post-harvest technologies and their processing, non-remunerative prices, wide gap between potential and actual production, absence of state incentives promoting bio-diesel as fuel, and economics and cost-benefit ratio.

Uncertainties brought about, by climate change as a result of continually rising greenhouse gas emission, coupled with fluctuating price of crude oil, tense relations among global nations, and rising energy needs, there has been a renewed focus on biofuels in recent years. Biofuels are clean, renewable sources of energy [1]. *J. curcas* has always been a top contender among all potential crop candidates for biofuels production since its seeds are abundant in extractable oil and can provide profitable yields in dry to semi-arid environments and on marginal soils [2, 3]. The oil is more efficient than diesel in pure, blended, and biodiesel forms and causes minimum smoke emission or engine damage [4]. *J. curcas* is widely planted in several countries, and commercial cultivation is being considered by many countries and institutions, including the World Bank [3]. The Indian government has also placed a high priority on *J. curcas* research, with plans to plant a large area of the crop in order to increase biofuel production in the coming years.

After being recognised as a greenhouse gas emissions (GHG) mitigation strategy under the Kyoto Protocol, global interest in carbon sequestered by agroforestry systems gained significant momentum. Comprehensive estimates of biomass and carbon stocks in plantations, including trees outside forests (TOFs), are required to prepare national roadmaps as a part of the commitment made under United Nations Framework Convention on Climate Change (UNFCCC). Furthermore, there is a growing interest in the market opportunities for forest carbon credits [5]. As plans are being implemented to expand *J. curcas* cultivation in large areas throughout the world, there is a need to assess the system's carbon sequestration capacity, which has received less attention than its oil production. This highlights the importance of developing methods to reliably assess the biomass production by the *J. curcas* system, as quantification of carbon in trees is heavily reliant on biomass estimation.

Biomass energy is a local energy source that can sufficiently meet the basic necessities of rural households. Though the contribution of biomass sources to the overall energy scenario is gradually decreasing, it still accounts for more than 40% of the country's energy supply. In rural areas, fuel-wood accounts for 65% of biomass

energy, agricultural waste accounts for 20%, and cow dung accounts for 15%. With the increased use of commercial energy sources, there has recently been a significant shift towards commercial sources. As a result, future energy projections in India do not show a proportionate increase in fuel-wood consumption with rising population. It is difficult to predict the fuel-mix shift at this juncture, but it is evident that it is happening in the right direction. Furthermore, in terms of global energy policy, the final form of energy is more important than the primary form. As a result, there has been a strong emphasis on how fuel-wood and other sources of energy can be converted into desirable forms, that are economically feasible, environmentally sound and energy efficient. This transformation is gradual but noticeable.

The Panchayat, or local self-government, is a body of elected citizens that work for the developmental goals and aspirations of the country at the grass root level (rural villages). According to the Eleventh Schedule of the Indian Constitution, certain developmental functions have been delegated to the Panchayats. The Panchayats are in charge of social forestry, farm forestry, land improvement, the implementation of land reforms, land consolidation and soil conservation, fuel and feed production, and non-conventional energy sources. To see how biomass production might be better regulated and regularised through local governance systems, one must analyse the energy policy and rural energy planning initiatives as well as the current programmes of the Indian government.

2. Current and future biofuels' demands

2.1 Global scenario

Demand of biofuels in the global market show distinct diversions between pre-pandemic and post pandemic period. COVID 19 pandemic plummeted the use of biofuels by 8.7% in 2020 relative to 2019. International Energy Agency projects global demand of biofuels to grow by 28% during 2021–2026. Conductive national policies, international commitments to adhere to binding agreements on climate and environment followed by ethanol -fuel blending mandates are expected to boost global biofuel market for 2021–2030. The recent ban on palm oil exports imposed by Indonesia, world's largest producer of palm oil, due to surge in domestic price and supply chain shock induced by Russia – Ukraine crisis have far-reaching ramifications in the demand, supply and use of biofuels by world nations. Nevertheless, demand of biofuels is expected to rise in long run due to the pertinent changes caused in the environment due to climate crisis, unfettered urbanisation at the cost of natural resources and socio-economic developmental goals of the nation states. International initiatives such as Roundtable on Sustainable Biomaterials (RSB), Sustainable Biofuels Consensus and Bonsucro also provide promising platforms to help take decisive actions to ensure both trade and use of biofuels.

2.2 State of biofuel requirement in India

India is ranked 3rd in the world for oil consumption, 20th for oil production globally, and imports nearly 87% of its oil consumption from different trade partners. India's crude oil production has been declining consistently since 2011–2012. India's crude oil imports dictated by expensive import bills coupled with national action plan to adhere to usage limits imposed by international climate agreements have

righteously streamlined the fuel sector to develop sustainable alternatives to crude oil. Development of Indigenous Cellulolytic Enzyme for the production of biofuels, and development and transferring of 2G Ethanol technology to Oil Marketing Companies (OMCs) by Department of Biotechnology in the Ministry of Science and Technology, Repurpose Used Cooking Oil (RUCO) launched by Food Safety and Standards Authority of India (FSSAI), Ethanol blending policy of the government to achieve 20% ethanol-blending and 5% biodiesel-blending by 2030 and reducing GST on ethanol for blending from 18–5% are steps mooted at different levels in the right direction to facilitate production, supply chain, sustainable trade and use of biofuels in the country. India's requirement of biofuels is henceforth expected to rise significantly for the decades to come.

2.3 National strategies and policies

2.3.1 National mission on oil seeds

India, being the largest consumer of edible oil in the world, imports more than half of its annual edible oil requirements, primarily from Indonesia, Malaysia, Brazil, Argentina, Russia and Ukraine. With the aim of increasing the acreage and production of oil seeds and oil palm in the country, Government of India launched National Edible Oil Mission-Oil Palm (NMEO-OP) in 2014. The centrally sponsored scheme targets to augment palm oil production from 3.1 lakh tonnes (2021) to 11.20 lakh tonnes by 2025–2026 and to 28 lakh tonnes by 2029–2030. The scheme also targets to increase the acreage of oil palm cultivation by an additional 6.5 lakh hectares by 2025–2026. Oil palm is a tropical crop thriving best in alluvial and moist loamy soils rich in organic matter that requires evenly distributed rainfall of around 3000–4000 mm per annum. Hence NMEO-OP has laid special emphasis to increase the acreage and productivity of oil palm in India's north-eastern states and the Andaman and Nicobar Islands due to favourable weather conditions. The mission is expected to copiously reduce our dependence on imports of oil palm and other oil seeds.

2.3.2 National policy on biofuels

National Policy on Biofuels, rolled out in 2018 streamlines India's ambitious target of becoming self-reliant nation at multifarious levels. The policy expands the ambit of substrates that can be used for producing bio-ethanol by permitting the use of sugar containing substances such as sweet sorghum, sugar beet and sugarcane juice, starch containing cassava and corn, broken or damaged food grains, and potatoes, unfit for human conception. It also classifies biofuels into three different categories vis-à-vis "basic biofuels" or "first generation biofuels" (1G) encompassing bioethanol and biodiesel and "advanced biofuels" or "second generation Biofuels" (2G) that includes ethanol, Municipal Solid Waste (MSW) to drop-in fuels, and "third generation (3G) biofuels" consisting of bio-CNG. The policy also makes it amenable, the use of surplus food grains for bio-ethanol production, thereby encouraging various supply chain mechanisms to boost up the production of biofuels. Recent amendments in the National Policy on Biofuels 2018, make it amenable to increase the scope of feed stocks required for production of biofuels and advances the Ethanol Blending Target (EBT) of 20% of petrol containing ethanol by 2025–2026 instead of 2030. Promotion

of use of biofuels in the transportation sector, not only reduces nation's crude import bill but also aligns the country in achieving Sustainable Development Goals (SDGs).

2.3.3 National agroforestry policy

Agroforestry is the scientific practice of integrating trees and shrubs in farm lands for increasing productivity, sustainability and diversity of the ecosystem as a whole. The beginning of the new millennium posed innumerable challenges to the development of Agroforestry by way of lack of institutional mechanisms, insufficient market infrastructure and incoherent legal provisions, which catalysed India in becoming the first country in the world to adopt a National Agroforestry Policy in 2014. The policy envisages the establishment of National Agroforestry Board to synergize and coordinate the efforts of different stakeholders at national level and to strengthen the livelihood opportunities of rural households through Agroforestry. The policy also achieves significant momentum as Agroforestry is known for its role in carbon sequestration, and achieve global climate goals.

3. *J. curcas* and *P. pinnata*

J. curcas is a multipurpose shrub belonging to the family of Euphorbiaceae. It is a tropical plant that can be developed as a commercial crop in farms or as a hedge along the edges of fields in regions with low to high rainfall. It is a plant with a wide range of benefits, including its acknowledged potential for the production of industrial biofuels. The plant can be planted as a live fence to enclose or keep out agricultural animals, as well as to manage erosion and reclaim degraded lands [1]. *J. curcas* is a robust and highly adaptable crop that may restore wastelands, including those that are being used for food crops [6]. *Jatropha* also thrives on marginal soils with low nutrient contents and is well adapted to well-drained and well-aerated soils [2]. *Jatropha* is promoted as a carbon sequestering crop in the current climate change scenario. The best choice is to have continued access to oil with the extra benefit of reducing greenhouse gas emissions. Although it is native to tropical America, it is extensively dispersed in semi-cultivated or wild areas throughout Africa, Central and South America, India, and South East Asia [7] and has been naturalised in the introduced environment. The oil from the *Jatropha* plant burns with a clear, smoke-free flame, hence it finds application in torches and lamps. Since it shares many of the desirable traits as diesel oil, inedible *Jatropha* vegetable oil is being investigated as a potential substitute. *Jatropha* has important implications for providing rural areas with energy services and can thus help in the search for workable alternatives to fossil fuels to reduce the amount of greenhouse gases in the atmosphere. These qualities, together with its adaptability, make it crucial for the progress of developing nations [8]. *J. curcas* exhibits a great deal of variety in its growth, production, and quality traits [9].

Arboreal legume *P. pinnata* (L.) Pierre belongs to the Millettieae tribe of the Papilionoideae subfamily. This medium-sized tree, which is native to the Indian subcontinent and south-east Asia, has been successfully introduced to humid tropical areas of the world, as well as in some areas of Australia, New Zealand, China, and the USA. Historically, traditional remedies, animal feed, green manure, wood, fish poison, and fuel have all been produced from this plant in India and its neighbouring regions. More significantly, *P. pinnata* is now acknowledged as a potential oil source for the developing biofuels sector. Currently, the tree crop is

widely grown throughout the humid low land tropics, as well as in Florida, Hawaii, Malaysia, Oceania, the Philippines, and the Seychelles [10]. A 10-year-old *P. pinnata* tree has a carbon sequestration capability of 74 kg, according to an estimate from ICRISAT-Hyderabad [11]. Periodic destructive sampling is the most accurate method for measuring and tracking the estimate of an above-ground biomass for a plant stand [12–14]. Unfortunately, it warrants time and labour to cut and weigh enough trees to accurately represent an ecosystem's size and species distribution. Destructive tree harvesting is cumbersome and labour-intensive [15–17]. Hence it necessitates long term R&D projects with regular monitoring and financial assistance.

4. Field experiments

The Hayatnagar Research Farm of the Central Research Institute for Dryland Agriculture (17.27°N latitude, 78.35°E longitude, and approximately 515 m above sea level), Hyderabad in the Southern part of India, served as the site for all experiments relating to morpho- and genetic variability, growth and reproductive biology, yield, crop improvement, and carbon sequestration potential. The semi-arid climate in the experimental site was marked by warm summers and moderate winters. The typical maximum air temperature varies between 13.5 and 16.8 degrees Celsius in the winter and 35.6 to 38.6 degrees Celsius in the summer (March, April, and May). The site experiences roughly 746.2 mm of annual long-term precipitation, primarily from June to October. The soil has a medium texture, is red, and has a shallow depth (Typic Haplustalf as per USDA soil classification).

4.1 Morpho- and genetic-variability in *J. curcas*

32 high-yielding candidate plus trees (CPTs) of *J. curcas* from various locations were collected for evaluating genetic association, variability in seed and growth characters, and latitudinal and longitudinal spread between 12°41' and 22°00' E longitude and 77° 00' and 84°40' N latitude covering 11 locations in an area spread of 150,000 km². In the progeny trial, significant trait differences were seen in all of the seed characters, including seed morphology and oil content, as well as in the growth characteristics, including plant height, the ratio of female to male flowers, and seed output.

The broad sense heritability was found to be high overall and exceeded 80% for all the examined seed attributes. Heritability for the female-to-male flower ratio was over 100%, followed by yield (83.61) and plant height (87.73). The path analysis showed that number of branches (0.612), days from fruiting to maturity (0.612), and the ratio of female to male flowers (0.789) had the strongest positive direct correlation with seed output (0.431). The number of days from flowering to fruiting had a negative indirect effect on yield. Ward's minimal variance cluster analysis' hierarchical clustering revealed phylo-geographic patterns in the genetic diversity. K-means clustering revealed that trees from different geographic regions were grouped together in a cluster and as were trees from the same geographical area placed in different clusters suggesting that geographical diversity did not go hand in hand with genetic diversity. In addition, clustering identified promising accession with favourable traits for future establishment of elite seedling seed orchard and clonal seed orchard for varietal and hybridization programmes (Table 1).

Parameters	Minimum	Maximum	Mean	SD
Plant Height (cm)	24.30	257.30	152.69	80.81
C.D (cm)	6.0	24.5	15.65	6.04
No. of Branches	24.0	243.0	149.33	76.72
Crown width (cm)	124.00	383.80	276.66	93.51
Crown depth (cm)	142.33	262.33	215.73	42.58

Table 1.
 Descriptive statistics of growth parameters of *Jatropha curcas*.

4.2 Morpho- and genetic-variability in *P. pinnata*

In order to evaluate genetic association and variability in seed and growth characters, 50 high yielding candidate plus trees (CPTs) of *P. pinnata* (L.) Pierre were collected from various locations within a latitudinal and longitudinal spread between 12°41 and 22°E longitude and 77°00 and 84°40N latitude, covering 11 locations in a spread of 150,000 km². Significant variations in plant height, number of branches, and seed form and oil content were also seen in the progeny trial. In comparison to seed traits, plant height and branch count showed substantially larger phenotypic and genotypic variance values. Oil content and seed length were the two seed parameters with the highest broad sense heritability (greater than 93% and 90.0%, respectively). In contrast, oil content displayed the largest genetic advance of 10.15%, while seed width displayed the second-highest genetic advance of 5.64%. By using Ward's Minimum Variance Cluster Analysis, phylo-geographic patterns of genetic diversity were revealed through hierarchical clustering. K means clustering showed that trees from the same geographic location were placed in distinct clusters, indicating that geographic diversity and genetic diversity are not correlated. Clustering also revealed prospective accessions with advantageous characteristics for the future establishment of orchards.

4.3 Evaluation trials of *J. curcas*

Ten elite lines of *J. curcas* (L.) vis-à-vis CRIDA-JJ-06, CRIDA-JL-06, CRIDA-JR-06, CSMCRI-C1, CSMCRI-C2, CSMCRI-C4, FRI-EL-1, NBPGR-0306, NBRI-J-05, and NBRI-J-18 were evaluated sequentially for 3 years (2007–2009) at CRIDA, Hyderabad, with the main objectives are to select superior plants with high seed and oil yields production and to study variation in agro-morphological, seed and oil yields characteristics. All attributes demonstrated significant variation among elite lines, according to analysis of variance. Although environment played a significant influence in the expression of these qualities, the broad sense heritability was high for all of the traits across years, showing that these traits were mostly regulated by genetic factors as opposed to environmental component. There were positive and highly significant correlations between the yield of seeds per plant and the yield of oil, pod weight, and pods per plant. Agro-morphological data-based cluster analysis was used to separate *Jatropha* lines into three groups using average linkage clustering. Clusters I, II, and III, respectively, included five, one, and four lines. The *Jatropha* populations showed highly significant genotypic differences for the variables investigated, and a strong genotype x environment interaction was observed for all traits. *Jatropha* lines differ

Genotypes	Seed yield (g/plant)	Oil yield (g/plant)	Pod Weight (g/plant)	East West Canopy	No. of primary branches	North South Canopy	Plant height (cm)	Pods / plant
CRIDAJJ06	449.36	143.82	520.86	195.90	79.35	195.52	200.50	225.79
CRIDAJL06	424.48	132.92	664.16	223.65	70.63	216.98	200.31	314.53
CRIDAJR06	434.63	138.20	540.92	205.15	82.06	221.25	202.87	285.25
CSMCRIC1	305.85	100.04	491.60	139.28	36.46	164.29	145.46	238.18
CSMCRIC2	327.06	101.97	443.82	201.54	69.50	216.52	177.31	198.09
CSMCRIC4	416.29	122.66	542.25	157.24	49.63	176.29	185.24	273.41
FRIEL1	435.30	153.90	550.81	193.54	73.25	221.95	196.86	323.09
NBPGR0306	410.67	133.38	575.79	163.42	90.50	172.47	199.54	230.80
NBRIJ05	320.99	83.13	478.28	183.13	81.48	194.17	213.29	206.33
NBRIJ18	288.04	111.45	413.24	163.19	94.48	159.69	186.14	207.87
Grand mean	381.27	122.15	522.17	182.60	72.73	193.91	190.75	250.33
CD (5%)	38.30	12.36	48.13	20.60	7.05	17.23	13.18	29.90
CV (%)	12.36	12.27	11.34	13.89	11.94	10.94	8.50	14.70

Table 2.

Comparative analysis of growth performance of elite lines of *Jatropha curcas*.

greatly from one another, so breeding attempts could employ these lines to improve the plant (Table 2).

Studies from other research groups on evaluation trials of *J. curcas* reported that both the phenotypic and genotypic coefficients of variation displayed a similar trend. 100-seed weight had the highest heritability (99%), followed by oil content (97%) and seed length (81%). Oil content and 100-seed weight showed a significant and positive connection ($r = 0.517$). Based on non-hierarchical K-Means cluster analysis, the *J. curcas* accessions were clearly divided into 6 clusters [18].

Prakash et al. [19] evaluated fifteen enzyme systems for their efficacy in distinguishing different accessions of *J. curcas* and it was found that twelve of them had fixed monomorphic alleles with no variation, while three (formate dehydrogenase, malate dehydrogenase, and peroxidase) were shown to be beneficial. The average number of polymorphic loci was 4, with a mean observed number of alleles per locus (A) of 1.533. Average observed heterozygosity (H_o) was 0.1082 and average anticipated heterozygosity (H_e) was 0.0993; gene flow (N_m) was 0.2177, indicating that there was little genetic variation between the different accessions, which may indicate that genes were not well segregated over generations.

Arolu [20] conducted similar evaluation trials in using 48 accessions of *J. curcas* from different locations of Malaysia and found that, with the exception of seed width, all of the morphological variables showed substantial levels of diversity and variation among the accessions. A positive and significant association between collar diameter, secondary branch count, and primary branch count was found. Additionally, a positive correlation between seed yield per ha, oil production per ha, and total number of seeds was found. With the exception of seed diameter and the number of major branches, high broad sense heritability was seen for all characteristics. The characteristic with the highest heritability was collar diameter (89.40%), and the one with the lowest value was seed width (−0.02%).

4.4 Carbon sequestration potential and allometric equations

Periodic destructive sampling is one of the most accurate methods for measuring and tracking the above-ground biomass for a stand [12, 13]. Unfortunately, it takes a lot of time and effort to cut and weigh enough trees to accurately represent the size and species distribution in a system. Destructive harvesting is labour-intensive and cumbersome [16, 17]. Additionally, it is challenging to harvest trees destructively for research projects because they last longer and require ongoing monitoring of the trees being studied. In order to ascertain the above-ground biomass of different tree species used in agroforestry and forests, non-destructive approaches have been devised. These techniques are based on regression models that connect biomass to allometric growth factors [21, 22]. As they may be immediately linked to remotely sensed data for the calculation of biomass in wider regions, creating allometric connections using crown area and/or tree height as predictors of biomass is also gaining interest.

For the development of prediction equations, allometric equations in tree biomass are often coupled to easily observed predictor variables, such as collar diameter/DBH and tree height. An effective allometric equation predicts the biomass of a tree without the requirement of destructive sampling. A frequently used predictor is the diameter at ground level (collar diameter) or breast height [23–25]. According to Ghezehei et al. [25], a power function is typically employed to establish the relationship between several characteristics relevant to tree growth [26].

$$\text{Biomass} = aX^b \quad (1)$$

Where ‘X’ is a predictor (collar diameter, tree height etc.)

b is a scaling exponent or allometric coefficient and a is an intercept.

In this study, the correlations between collar diameter and biomass, tree height and biomass, and branch number and biomass are established using the aforementioned power function. The biomass, crown depth, and crown breadth were linearized in the aforementioned model. For total above, total below, and total (above + below) dry biomass, allometric equations were created. This method was employed to enable comparison with already-existing equations and to assess which equation yields more trustworthy findings. Using both sides of the logarithmic transformation.

$$\log (\text{biomass}) = (\log a) + b (\log X). \quad (2)$$

By applying linear regression in SPSS (version IBM SPSS Statistics 19), the parameters of the linearized allometric equations (b and log a) were computed. In the end, the antilog function was used to compute the original parameter “a”. The R² value, the F-statistic, and a scatter plot of the residuals were used to assess the significance and validity of the established equations. Microsoft Excel was employed to visualise the equation graphs. An independent dataset containing the data from 320 trees of varying ages and under diverse management settings was used to validate the proposed equations.

4.4.1 Carbon sequestration potential of *J. curcas*

One of our studies involved developing allometric relationships in the *Jatropha* plant to forecast several biomass-related components (above ground and below ground) using easily quantifiable characteristics, such as collar diameter, tree height, number of branches, crown diameter, and crown depth. Additionally, it was

intended to demonstrate the validity of these associations using a separate dataset collected from a variety of managerial scenarios. In 2011, during the wet season, destructive sampling was done on *Jatropha* plants that were 8 years old. When predicting different biomass components (above, below, and total) using easily observable variables, highly significant allometric associations (F values significant at 1% level) were found with R^2 values ranging from 0.89 to 0.98. Of all the predictors, collar diameter exhibited a highly significant relationship with total dry biomass per plant ($R^2 = 0.97$). The allometric relationships developed were validated with an independent dataset.

An independent dataset comprising of 220 trees with a suitable dendro-chronological range (2 years to 8 years) and management settings (various fertiliser and irrigation regimes) was used to validate the allometric connections. For the 220 trees, allometric relationships using collar diameter as the explanatory variable were utilised to forecast the number of branches. The number of branches-collar diameter allometric equation was found to be valid since the observed and predicted values show a high degree of agreement. Power regressions accurately depict tree allometry in a number of trees [27]. They enable the use of conventional least squares regression analysis and give uniformity of variance over the sampled range after log translation [25]. After the log transformation, a correction factor was applied in some research to lessen the systematic bias, and equations based on the correction factor were developed. However, because the computed F ratios are very significant and the R^2 values are greater than 0.90 at the 1% level of significance in our investigation, we did not utilise any correction factor. It implies that our study had little systematic bias. Estimates for some of the trees have become more accurate, thanks to the use of tree height and breast height diameter. However, as shown by collar diameter-based relationships, in the current study collar diameter alone was sufficient to reliably predict various tree development characteristics, including above ground, below ground, and total biomass.

In the current study, there is a consistent and significant allometric association between crown depth and the other growth characteristics. This went against several of the earlier findings [28]. Similar to this, animal browsing and seasonal deciduousness have an impact on some trees' biomass of leaves. In Hyderabad's semi-arid climate, we noticed that *Jatropha* trees lose their leaves in December and stay leafless from December through February. Beginning in the month of March, the leaves start to grow. Therefore, during periods when leaf drop does not occur, the equations for the estimate of leaf biomass are to be applied (**Table 3**).

Diameter Classes	Above dry ground dry biomass t/ha	Below ground dry biomass t/ha	Total dry t/ha (A + B)	Total C biomass t/ha (a + b)
D1 (5–10 cm)	3.10	2.23	5.33	2.56
D2 (10–15 cm)	14.28	4.28	18.56	7.84
D3 (15–20 cm)	16.19	5.32	21.51	9.12
D4 (20–25 cm)	18.44	5.56	24.00	10.08
Average	13.00	4.35	17.35	7.36

Table 3.
Jatropha curcas dry biomass and carbon biomass.

4.4.2 Evaluation trials of *P. pinnata*

In a study, Sharma et al. [29] investigated the molecular genetic diversity of 46 accessions of *P. pinnata* gathered from six different Indian states. They discovered that 520 identifiable fragments, of which 502 (96.5%) were polymorphic, were produced by 5 AFLP primer combinations. Four factors—polymorphism information content (PIC), effective multiplex ratio (EMR), marker index (MI), and resolving power—were evaluated to determine how informative an AFLP primer is (RP). A total of 51 distinct fragments were found, of which 19 distinct fragments were found using the primer pair E-ACG/M-CTA. Even though the neighbour joining (NJ) method did not strictly classify accessions according to the region in which they were collected, a high level of genetic diversity was found in the tested germplasm.

Patil et al. [30] conducted a comparative study on the biodiesel and bioproductive parameters of *J. curcas* and *P. pinnata*. The variation of bioproductivity and biodiesel parameters of both plants were compared every 6 months for years and analysed with variance and correlation coefficient by Pearson's method using Graphpad instat 3.06 software (Windows and Mac). *P. pinnata* has better germination rate (71%), 100 pod weight (PW) (311.59 g) and 100 seed weight (SW) (173.6 g) compared to *J. curcas* germination rate (3.2%), 100 pod weight (111.29). g) and 100 SW (67.6 g). *P. pinnata* has a strong correlation between plant height and crown growth (CG) (0.98), neck diameter (CD) (0.99), number of branches per plant (NBP) (0.995) and number of leaves per branch (NLB) (0.862) compared to *J. curcas* which showed a good correlation between plant height and CG (0.976), CD (0.970), NBP (0.988), NLB (0.920) and number of pods per branch (0.657). However, *J. curcas* presented a negative correlation between beam width and seed length (SL) (−0.7), seed width (−0.28) and seed thickness (ST) (−0.36) and 100 PW and SL (−0.199). ST (−0.220) and 100 SW (−0.70). For each litre of crude oil, approximately kg of *P. pinnata* seeds were consumed, yielding 896 mL of biodiesel when trans-esterified, compared to 5.66 kg of *J. curcas* seeds per litre of crude oil, yielding approximately 663 mL of biodiesel.

4.4.3 Carbon sequestration potential of *P. pinnata*

Additionally, the study established allometric relationships in *P. pinnata* between biomass and the readily measurable characteristics (collar diameter, tree height, number of branches, crown diameter, and depth), and it tested the validity of these relationships using a separate dataset from various management scenarios. Plants were 9 years old when destructive sampling was done in the months of January through March 2012.

Using the collar diameter ($R^2 > 0.96$), plant height ($R^2 > 0.94$), number of branches ($R^2 > 0.91$), crown width ($R^2 > 0.96$), and crown depth ($R^2 > 0.65$), highly significant allometric associations (F values significant at 1% level) were developed. An independent dataset was used to validate the associations that were developed. Independent datasets from 320 trees with diverse age group (2 years to 9 years) and management (different fertilisation, irrigation, grafting, and seedling generated plants) circumstances were used to assess the allometric relationships. The correlation coefficient was high and positive ($R^2 > 0.917$ and $R^2 > 0.978$), indicating that the link was linear. As the independent data sets comprised a variety of ages, management situations, and development settings, the results substantially support the validity of the height-collar diameter and number of branches-collar diameter equations (Table 4).

Diameter Classes	Above dry ground dry biomass t/ha	Below ground dry biomass t/ha	Total dry t/ha (A + B)	Total C biomass t/ha (a + b)
D1 (0–5 cm)	2.17	2.16	4.33	1.87
D2 (5–10 cm)	11.36	11.40	22.76	9.80
D3 (10–15 cm)	27.79	22.45	50.24	21.72
D4 (15–20 cm)	42.31	38.49	80.81	34.85
Average	20.91	18.63	39.54	17.06

Table 4.*P. pinnata* dry biomass and carbon biomass.

For a number of tree species, species-specific allometric equations have been devised [31, 32]. Such *Jatropha* equations, however, are limited and unavailable, especially for Indian circumstances. Allometry places a lot of focus on quantifying above-ground biomass rather than below-ground biomass because the latter is laborious and time-consuming. There is a steady requirement to create allometric equations of *Jatropha* because it is suggested that the species be widely planted in semi-arid regions of India. In the absence of site-specific or generalised equations, equations created elsewhere may be taken into consideration for usage at a site [33]. However, for *Jatropha*, there are very few published equations, and even fewer for the quantification of below-ground biomass. For trees like *Jatropha*, the development of allometric correlations is particularly difficult due to their complicated form-function relationships, defoliation, and change in leaf phenology during dry seasons, which is especially noticeable in younger trees [34]. There is a knowledge gap regarding accurate and thorough estimates of *Jatropha* biomass, despite new scientific knowledge on utility features [35], genetic diversity assessment [36], and yield [37] being developed. As a result, research was done with the aim of developing allometric equations and validating them using a large, independent dataset that represented various management settings.

5. Successful agroforestry models

5.1 Pongamia: *Macrotyloma uniflorum* (horse gram) based agroforestry model

A study utilising *P. pinnata* as main crop and *M. uniflorum* (Horse gram) as intercrop were carried out to know the yield patterns in these two crops in varied spacings. *P. pinnata* was sown in 2003 in 3 different spacings of 6×4 m, 6×6 m and 6×8 m, though 6×6 m is general recommendation, which was used as the check for the study. In 2007 (at the end of 4th year of plantation), Kernel yield of *P. pinnata* in recommended spacing (check) of 6×6 m was found to be high (0.38 kg/tree) though the intercropped *M. uniflorum* yield is minimum (2.9 q/ha) as compared to spacing of *P. pinnata* with 6×4 m which yielded 0.01 kg/tree that translates to 97.4% and in 6×8 m which yielded 0.02 kg/tree or about 94.7% as compared to recommended spacing (check). The intercropped yield of Horse gram in 2007 was 3.3 and 4.3 q/ha under 6×4 m and 6×8 m spacing respectively showing an increase of 13.8% and 48.3% over the yields of *M. uniflorum* obtained in 6×6 m (2.9 q/ha). However, in 2008 also like in 2007, the kernel yield of *P. pinnata* in recommended spacing was the highest (1.88 kg/tree) as compared to 6×4 m which yielded 1.02 kg/tree ie. –45.7%

while in 6×8 m it yielded 0.18 kg/tree ie. –90.4% as compared to recommended spacing (check). These results indicate the impact of intercropping under recommended spacing for enhanced yield of *P. pinnata*. The area (ha), production (ha) and productivity (kg/ha) of *P. pinnata* in India are 1702.9, 719.5 and 423 respectively while in the state of Andhra Pradesh in India, these are 272.5, 76.3 and 280 respectively. *M. uniflorum* is also a bankable contingent crop. It is beneficial in curing cough, breathing illness arising due to flatulation, hiccups, stones and fever. It also helps eliminate germs and worms from the body.

Both the main crop *P. pinnata* as well as the intercrop *M. uniflorum* are drought tolerant legumes with nitrogen fixing ability to the soil. Hence the study underscored that an agroforestry model with a tree legume and a crop legume would be very beneficial in dry lands and wastelands as land reclamation and rejuvenation happens through soil-enriching legumes. However, to balance between the food cropped area with these biofuels the best option would be intercropping for sustaining the nutrition security of human and animal populations along with the biofuel oils within a given area. This intercropping would also serve as a risk aversion strategy in providing nutritional security and/or as a crop of economic value during the early stages of the growth of *P. pinnata*. Since the full potential growth of *P. pinnata* takes 7 years, intercropping especially with pulses would benefit the main crop through means of root nodulation, and leaf fall thereby enhancing the soil fertility.

The above results on intercropping with legume based biofuel tree and grain legume may be recommended in arid and semi-arid drought prone areas, watersheds and wastelands for sustainable realisation of the renewable source of energy through the biofuel oil yielding tree *P. pinnata* along with the arid and semiarid grain legume *M. uniflorum* for sustaining the nutritional security of animals and humans.

5.2 J. curcas: *Cajanus cajan* (Redgram) based agroforestry model

Three best genotypes (Jabua, CRIDA-Utnoor & Raipur) based on seed yield and oil content in seed were selected from a total of 102 genotypes were selected for the study. These accessions were collected from the states of Andhra Pradesh, Madhya Pradesh and Chhattisgarh during 2002–2003 and planted in 2003 July at Research farm of CRIDA, Hyderabad.

The date of sowing of main crop *J. curcas* was 18.09.2003. With the spacing of $3 \text{ m} \times 3 \text{ m}$ a population of 1111 plants was accommodated in each hectare. Total plot size under Jabua, CRIDA-Utnoor & Raipur varieties of *Jatropha* with $3 \text{ m} \times 3 \text{ m}$ was 1620 m^2 , 2160 m^2 and 2160 m^2 respectively. Thus the total plot size under main crop was 5940 m^2 . Number of plants accommodated under Jabua, CRIDA-Utnoor and Raipur were 180, 240 and 240 respectively. Thus the total plant population under these three varieties was 660. *C. cajan* was taken as intercrop in all the three genotypes during 2004. Sowing of *C. cajan*, variety ICPL-85063 (Lakshmi) was done on 14th July during 2004 with spacing of $60 \text{ cm} \times 10 \text{ cm}$. Number of plants of *J. curcas* and *C. cajan* per hectare area was 1111 and 1667 respectively. At the time of sowing fertilisers of 40 kg N and 50 kg P_2O_5 per hectare were applied. Harvesting of *C. cajan* was done on 20th November 2004.

The primary treatments of pruning were effected in January 2004, which was dormant stage. In each of the three test genotypes of *J. curcas*, three ground level pruning treatments viz. 30 cm, 45 cm and 60 cm were affected along with the unpruned control. The seed yields of the control as well as the three pruning treatments were recorded during 2005, 2006 and 2007.

The study reaffirmed the fact that *Jatropha* is an easy to establish crop, grows relatively quickly and is hardy and drought tolerant [38]. Highest yield of legume intercrop was obtained in CRIDA-Utnoor genotype of *J. curcas*, which was also the highest seed yielder. Thus *J. curcas*–*C. cajan* based Agroforestry Model may be recommended in semi-arid to arid regions that can be brought under eco restoration efforts not only for biodiesel production but also to increase global green cover.

6. Sustainability model for addressing rural energy needs

6.1 Ecosystem subsidies

Nature has its own ways that determine the flow of nutrients, energy and organic matter among different ecosystems. All such resource flows which augment the population of consumers in the ecosystem are called ecological subsidies. Conventional sources such as fossil fuels and curated fuels such as petrol and diesel depreciate the natural energy flow of any ecosystem by polluting the environment and clogging sensitive physiological receptors of plants while biofuels present a sustainable alternative. *J. curcas* and *P. pinnata* plantations add large amount of organic matter through fallen leaves and biomass, it helps to improve the microbial biological activity hence catalysing the flow of nutrients between different ecosystems.

6.2 Restoration of wastelands

Restoration of degraded lands and combating desertification have been in the forefront of national priorities since 1980s, the significance of which have mounted due to inclement weather, climate crisis and the imminent threat of global warming. In 2003–2005, 94.53 million hectares (mha) of land underwent land degradation, which gradually increased to 96.40 mha in 2011–2013 and 97.85 million hectares in 2018–2019. Main reasons attributed to the degradation include loss of soil cover, vegetation loss, and wind and water erosion taken atop by climate crisis. India aims to restore 26 million hectares of degraded land by 2030 and is also working towards achieving its national commitment on Land Degradation Neutrality (LDN). National Afforestation Programme implemented since 2000, National Action Programme to Combat Desertification (2001), National Mission on Green India and commitment laid towards Bonn's Challenge calls for immediate intervention to elbow out the crisis of land degradation.

Results of a study on carbon sequestration potential and greenhouse gas emissions in *J. curcas* and *P. pinnata* show that these TBOs grown on dry lands have the potential to add large quantities of carbon (0.3% - 1.7% in *J. curcas* and 0.3% - 0.48% in *P. pinnata*) in addition to that accumulated by the standing crop. Increased carbon content in the soil augment the growth of beneficial microbes which in turn improves the soil fertility, productivity and ecological subsidies of the landscape.

6.3 Reducing carbon emission and working towards climate goals

Recently, at the 26th Conference of Parties (COP 26) Climate Summit held at Glasgow, India pledged to attain carbon neutrality by 2070 as part of a 5-point action plan that included reducing emissions to 50 percent by 2030. The role of vegetation (terrestrial and aquatic) in sequestering carbon and thereby reducing the emissions

are widely acknowledged and taken forward through afforestation programmes. Certain plants such as *J. curcas* and *P. pinnata* have a higher rate of sequestration of carbon. Research shows that a nine-year-old *J. curcas* and *P. pinnata* can respectively sequester 7.36 tonnes/hectare and 17.06 tonnes/hectare of carbon per annum (my paper reference). Carbon di oxide mitigation potential of a nine-year-old *J. curcas* and *P. pinnata* respectively accounted to 31.54 tonnes/hectare and 50.18 tonnes/hectare, which exemplifies the role of *J. curcas* and *P. pinnata* in mitigating the effects of a major greenhouse gas. Adoption of *P. pinnata* and *J. curcas* either as monoculture plantations or as components in agroforestry models not only support biodiesel production but aid in our attempt to cut down emissions and achieve climate goals within the pledged deadline.

7. Conclusion

The policies for encouraging the plantation of tree-based biofuels are focused on the use of wastelands and less productive regions. In light of stagnant food crops production and burgeoning domestic demand for food grains, use of food crops for biofuels production remains as question, as it competes with the crops for scare land and water resources. Additionally, India's policy of neither allowing nor encouraging the use of food or other feedstock for the production of biofuels is based on the fact that food inflation has been steadily rising over the past few years. As a result, the nation's biofuel project must carefully navigate through sensitive local and international issues. Climate Financing is a major hurdle caught between bureaucratic red tapism and false promises made by developed countries. Without adequate finance and policy support, technologies cease to transfer from lab to land. India also urged the developed countries to deliver on their promises of climate financing at the recently concluded COP 26 Climate Summit at Glasgow. Biofuel subsidies are already in place in United States and European Union to facilitate farmers facing low prices for their crops. Subsidies in the form of incentives need to be provided for start-ups that venture into biofuel crops farming, biofuel production and supply. Such incentives not only boost up the green start-ups but also motivates entrepreneurs to invest in such businesses which synergizes our effort to attain carbon neutrality by 2070.

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