Castor Bean

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Castor bean (*Ricinus communis* L.) is an unpalatable tropical plant belonging to the spurge family (Euphorbiaceae). It has great phytoremediation potential and is used for biofuels production. Its cultivation on contaminated and marginal land can be considered a great alternative to fossil fuel, lowering the social-economic implication and ecological impacts of biodiesel production. In this entry, we analyze the botanical, agronomical, and the by-product obtainable from castor bean. More information about the castor bean phytoremediation potential and its resistance to abiotic stresses can be found at 10.3390/agronomy10111690

Ricinus communis, Castor bean Agronomy Biodiesel

Castor bean (*Ricinus communis* L.) is a tropical plant with C3 metabolism belonging to the spurge family (Euphorbiaceae), genus *Ricinus*, with numerous wild and semiwild types that differ genotypically and phenotypically.

1. Botanical Aspects

Castor bean can be as short as two feet in height (1.5–2.4 m), especially in a temperate climate, or as tall as a moderate-sized tree in tropical and subtropical areas (10–13 m) [1] [2]. In Ethiopia, where it is thought to have originated, plant size varies from a perennial tree or shrub to a small annual [2] [3]. The leaves are palmate with 5–11 lobes and alternate; they are often dark glossy green, but the color can vary from light green to dark red, depending on the anthocyanin level and genotype [3] [4]. The fruit is a spiny, greenish to reddish-purple capsule with three locules containing one oval, shiny, and highly poisonous brownish seed with marble-gray marks and a light-brown caruncle [4] [5]; at maturity, the capsules are dried and may have dehiscence, depending on the genotype [6]. Some castor bean varieties can produce capsules with rudimentary spines, whereas others produce soft, flexible, and nonirritant spiny capsules, and others produce spiny irritant capsules [4]. The seeds of castor bean grow inside capsules on raceme that develops progressively over the life of the plant. Seeds, exposed to different environmental conditions, end in an inhomogeneous maturity, with different developmental stages among the raceme and their order [6] [7]. The seeds can differ in color, size, external markings, weight, and shape between cultivars [3] [8] [9] [10]; however, they are of an oval form on average. The number of capsules per raceme depends on the number of female flowers on it. Male flowers are yellowish-green with creamy stamens, while female flowers lie in undeveloped spiny capsules with prominent red stigmas. Castor bean plants can be “normal monoecious” with pistillate flowers on the upper part of the raceme and staminate flowers on the lower part or "interspersed monoecious" with pistillate and staminate flowers interspersed along the entire raceme axis [4] [5] [6] [7]. Rarely, castor bean inflorescence can terminate with a hermaphrodite flower that regularly drops off before capsule setting [1]. The female and male flower proportion on the raceme can vary within and among genotypes [5], and it is extensively influenced by the environment. Racemes can have different shapes (conical, cylindrical, or oval) with different capsule arrangements, which can be compact, semi-compact, or loose [4]. According to the order of manifestation, the racemes are called primary, secondary, or tertiary, and their numbers increase geometrically with the number of branches [6]. The castor bean stem is round, sometimes covered with a waxy bloom, and it may be green, reddish, or purple [4]. The dark-purple stem and the sulfur-yellow colors are occasional [3].

Figure 1. *Ricinus communis* L. (CB).

2. Ecological Niche

Castor bean can grow well in a wide range of ecosystems, from temperate to tropical desert and wet forests [11], in a range of 250–4250 mm annual precipitation [2] [12], and in a wide range (4.5–8.3) of soil pH [3]. Considered a wasteland colonizer plant, it is commonly found on landfills, railway tracks, roadsides, etc. Castor bean cultivation spreads to 40° north (N) and 40° south (S) latitudes, but some cultivars have been found at 52° N in Russia [5]. It can grow from sea level to more than 2000 m above sea level (a.s.l.) [1], but the optimal altitude is 300–1800 m a.s.l. [5].

3. Agronomic Features

3.1. Growth Requirements

Castor bean requires temperatures between 20 and 26 ◦C [13]; shoots die at temperatures below −1 ◦C and adult plants die at −3 ◦C [3]. Castor bean requires a frost-free period of 140–180 days and at least 140 days with mean temperature between 20◦ and 27 ◦C for satisfactory yields [1] [2] (Table 2). Castor bean grows in all kinds of soils but prefers a well-drained moisture-retentive soil such as sandy loam [4]. Castor bean cultivation necessitates fertile, well-aerated soils with a pH of 6–7.3 and rainfall of 600–700 mm for optimum yield [4]. Castor bean is a long-day plant, but is adaptable to a wide range of photoperiods even if with reduced yields [4]. The optimal relative air humidity range falls between 30% and 60% [3], with low relative humidity in the growth phase to obtain maximum productivity; humid and cloudy days, despite the temperature, can be reflected in lower seed yield [13].

Table 1. Average seed and oil yield of castor bean in different countries under different treatments. USA, United States of America; n.s., not specified.

Country	Site	Seed Yield Mg/ha	Oil Yield Mg/ha	Genotype	Treatment	Reference
Ethiopia	Rift Valley	1.2–1.4	0.6–0.7	Hiruy	Planting density	[14]
Greece	Aliartos	3.0–3.8	n.s.	Kaima 93, C-853, C-855, C-856, C-864, C-1002, C-1008	Genotype evaluation (year 2014)	[15]
Italy	Cadriano	0.7–4.0	n.s.	C-855, C-856, C-857, C-864, C-1008	Genotype evaluation (year 2014)	[15]

Italy	Ragusa	0.7–7.3	0.3–3.3	Local 1, Local 2, Brazil, Tunisia	Autumnal sowings	[12]
Mexico	Texcoco	2.6–5.2	n.s.	Krishna, Rincon	Optimal soil moisture	[16]
Colombia	Cordoba	0.8–1.2	0.3–0.6	Monteira, Cienaga de Oro, Los Cordobas, BRS Nordestina	Planting density	[17]
USA	Florida, Citra	0.7–1.3	0.3–0.6	Birminghan, Hale	Plant growth regulator and harvest aid	[18]
USA	Florida, Jay	0.7–1.2	0.3–0.6	Birminghan, Hale	Plant growth regulator and harvest aid	[18]
Italy	Sardinia	1.4–2.5	n.s.	Hazera 22, ISCIOR 101	Irrigation	[19]
USA	Texas	0.2–2.7	n.s.	BRS Nordestina	Irrigation	[20]
Brazil	Carnaubais	0.1–1.2	n.s.	BRS Nordestina	Fertilization	[21]

Pakistan	Bahawalpur	1.2–2.4	n.s.	DS-30	Fertilization	[22]

Castor bean has slow and cold-sensitive germination [13]. Seeds (Figure 2) may have a dormancy period of several months, depending on variety, while others can germinate from freshly harvested seeds without any treatment [20]. The base temperature for CB seed emergence was found to be 15 ◦C, optimum at 31 ◦C and maximum at 35–36 ◦C, requiring 464 degree-days after pollination to reach physiological maturity [3] [23] [24].

Figure 2. *Ricinus communis* L. seeds.

3.2. Planting Density

Plant arrangement is a simple low-cost technology that can affect yield [1],[25], ranging from 4200 plants/ha for tall cultivars to 70,000 plants/ha for dwarf varieties [26]. Castor bean plants compensate for a low population density by producing a higher number of racemes [27] [28] which, however, do not increase the seed yield considering the reduced number of plants per hectare [29]. Lower plant population increases basal stem diameter and survival rate [25] [28] [30]. Seed number, a highly hereditable characteristic, is hardly influenced by environmental or exogenous factors [25]. The raceme size is slightly influenced by plant density [25] [28]. In all the aforementioned studies, oil content, oil yield, and oil quality were not influenced by plant density [17].

3.3. Irrigation

Castor bean is very sensitive to root hypoxia caused by soil flooding; irreversible damage occurs after just 3 days of flooding [24]. The deep taproots and extensive root systems enable the plant to take up water from deep soil layers and allow seed production with little or no irrigation. Obviously, despite the adaptability of CB to drought, the greatest yields are obtained with irrigation. There is almost a linear increase in seed yield with irrigation, nearly

doubling when additional water is supplied [19] [31]. In Brazil, a rainfed (376 mm) CB field produced 1774 kg/ha of seeds, +24% with supplementary irrigation (1099 mm), and +139% with 1662 mm of water supplied [32]. The castor bean plant response in seed yield to water treatments differs between cultivars, but most of the variation can be explained by the number of racemes, followed by seeds per raceme and seed weight [19] [33]. The seed yield increase in irrigated CB fields is small compared with that of other common crops cultivated in the same area, suggesting that it is more suitable for low-input, arid environments [16] [19] [34]. Castor bean can also grow well with wastewater irrigation [3] [35] [36]. Wastewater is an alternative water source
being recently exploited to irrigate biofuel crops without depleting the already scarce water resources. A study by Tsoutsos et al. [37] investigated the use of wastewater on the quality of castor bean oil and biodiesel production. Oil samples derived from wastewater irrigation provided a lower concentration of free fatty acids and a slight reduction in viscosity. According to Abbas et al. [38], irrigation with wastewater resulted in higher fresh and dry weights of castor bean roots, shoots, leaves, and seeds (g/plant) than those irrigated with freshwater, due to nutritive element contents such as N, P, and K.

3.4. Fertilization

CB can doubtlessly grow on agriculturally marginal lands; however, it benefits considerably from the addition of fertilizer. For example, nitrogen applications can increase seed yield by 114% compared to unfertilized plants [30] [39]. Organic fertilization can increase productivity by 458 kg/ha, mineral fertilization by 824 kg/ha, and the combination of organic fertilization and mineral by 1009 kg/ha. Mineral fertilization with N, P, and K, with the addition of organic material,
contributed to an increase in productivity of 184 kg/ha [21]. Unfertilized plants produced 46% less fruit compared to well-fertilized ones, with a 50% decrease in fruit dry weight [40]. However, CB plants selected to grow at a certain nutrient level have been adapted to produce the maximum at that level [39]; when cultivated in very fertile soils, they tend to produce large vegetative mass at the expense of seed production. The oil content in seeds seemed to increase only in response to P and was not influenced by other nutrients [39]. Among the organic fertilizers, poultry manure seemed to be most effective [41].

4. Castor Bean Products

Castor bean has been used for a very long time and is one of the oldest commercial products [42], known in the traditional medicine of ancient Mediterranean and Asian cultures [43], and still used in traditional medicine worldwide (e.g., Chinese and Ayurveda) [1] [43]. Long before “biobased” became a catchphrase, CB oil-derived products were used for centuries (e.g., in ancient Egypt lamps) [1] [44]. Currently, CB oil has more than 700 industrial uses, and its global demand is increasing steadily by 3–5% per year [45]. It is a well-recognized commodity with a well-established market, costing 2–3 times more than soybean oil being cultivated only in a few countries [1]. Castor bean oil consists mainly of ricinoleic acid (85–90%), a hydroxylated fatty acid with one double bond, and some unique properties. Castor bean has an oil close to a technical grade of purity, a rare natural phenomenon [1] [46]. It is more versatile than other vegetable oils and extensively used in a variety of industries, such as the cosmetic and pharmaceutical industries, as well as in paint, varnish, and lacquer production [47] [48]. Because of its high viscosity, it is used as a lubricant in two-stroke engines, neat or blended, reducing smoke emissions by up to 50–70% [49] [50]. It is a polyol that can readily form polymers making polyurethanes that find applications in adhesives and coatings, electrical insulators, and semirigid foams used in thermal insulation [51]; it was also suggested as a possible candidate biomaterial for wound dressings [52] and as a graft for bone defect treatments [53]. The so-called Turkey red oil, produced by CB oil sulfation, is widely used in textile industries in dyeing and in finishing cotton and linen [54]. The CB oil obtained mechanically by pressing results in CB cake, while CB meal derives from CB oil production through solvents. CB cake is a good organic fertilizer, containing about 5.5% nitrogen, 1.8–1.9% phosphorus, and 1.1% potassium [55] [56]. It can be applied in moist soil 3 weeks before sowing the crops, allowing for toxicant degradation [57]. It has been used as a substrate for tomato seedlings and as a fertilizer for onion production [58] [59].

Castor bean cake has also shown great potential for biogas production and was found to be a very interesting feedstock
for the production of pyrolysis bio-oil [60] [61]. According to Gonzalez-Chavez et al. [62], castor bean cake derived from plants naturally established on polluted mine-tailings can be utilized as organic fertilizer due to the lower levels (e.g., Pb in cake: 2.6–8.8 mg·kg−1) of metal contamination allowed by EU regulations (e.g., maximum limit values of Pb in organic fertilizer: 120 mg·kg−1 of dry matter) [63]. Castor bean meal may contain up to 55.8% crude protein and can be used as a protein source for animal feedstock [64]. Due to its ricin content, CB meal use necessitates caution. Different types of
seed processing can reduce or eliminate this toxin [65] [66]. For instance, it can be detoxified with calcium oxide replacing up to 50% of soybean meal in lambs' diet [64] and reducing the production costs in a beef cattle grazing system [67]. Furthermore, up to 15% non-detoxified CB meal can be used in goat feed [68]. Castor bean can also be considered an eco-friendly and economic alternative to synthetic insecticidal agents (e.g., against *Spodotpera frugiperda*, *Spodoptera littoralis, Musca domestica*, and *Phlebotomus duboscqi*, the Leishmania vector) [69] [70] [71]. Leaf extracts have also shown antimicrobial potential and antifungal activity [72] [73] [74]. Castor bean leaves are used, especially in India and Africa [75] [76], as food for *Samia cynthia*, a moth used to produce silk; in Italy, the use of senescent leaves for the eri-silkworm artificial diet has provided a promising opportunity for valorizing residual biomass to good use after biorefinery [77]. Moreover, the reactive surface of CB leaf powder has been studied as a green adsorbent for the removal of heavy metals from natural river water [78]. In the eastern part of Nigeria, CB seeds are used as food seasoning called Ogiri, and CB can be used in honey production [13] [48].

4.1. Castor Bean Biodiesel

Recently, castor bean biodiesel is receiving great attention [79]. Biodiesel is the alcoholic ester of vegetable oils obtained via transesterification. It presents many advantages over fuel, e.g., nontoxicity, biodegradability, renewability, and a decline in most exhaust emissions. For instance, the presence of oxygen in biodiesel makes it burn cleaner, and its higher viscosity cancels the need for added sulfur compounds in diesel, reducing SO_2 emissions [80] [81]. Biodiesel production begins with vegetable oil extraction from the seeds, generally carried out with mechanical pressing, solvent extraction, or a combination of both technologies [81]. Supercritical fluids, ultrasound, and microwave are the newest technologies developed for oil extraction [81]. After oil extraction, some refining steps are carried out to improve biodiesel quality, such as filtration or discoloration [81]. Subsequently, biodiesel is obtained through the transformation of triglycerides into fatty acids (FA), which can be performed with ethanol (resulting in fatty acid ethyl esters, FAEEs) or methanol (fatty acid methyl esters, FAMEs), in the presence of catalysts that can be chemical (alkali or acid catalysts) or biological (enzymes) [82]. Afterward, separation by centrifugation or decantation is performed to decrease the impurities and recover all products (biodiesel, solvent, and glycerol) [81]. The fatty acid composition of the feedstock, its properties, and the production process employed are the parameters mainly affecting biodiesel quality [83]. The biodiesel obtained, used alone or blended with petrodiesel, has to conform to specific standards, e.g., ASTM D6751 or EN 14214 [81] [84]. Some important biodiesel properties that need to conform to standards are kinetic viscosity, cetane number, cloud and pour point, and flashpoint.

Castor bean oil is mainly composed of ricinoleic acid (85–90%). Castor bean has a very high percentage of seed oil content (40–55%), higher than other normally used oil crops such as soybean (15–20%), sunflower (25–35%), or rapeseed (38–46%), with a cultivation cost reduced by up to 50% compared to rapeseed [79]. Castor bean oil can be used in diesel engines with few modifications [85] [86], lowering the level of pollutants, carcinogens, and greenhouse gasses [80] [81]. According to Anjani [3], about 79,782 Mg of CO_2 emission can be saved if 10% of total castor bean seed oil produced is transesterified into biodiesel. The world average castor bean seed production is 1.1 Mg/ha, corresponding to 460 kg of castor bean oil with a seed oil content of 47% and oil yield of 90%; however, a higher yield can be obtained, indicating promising oil productivity [46] [86]. Castor bean oil FAMEs present an unacceptably high value of kinematic viscosity (which influences characteristics such as the amount of fuel that drips in the injection pump [82]) and low cetane number (which quantifies the time between injection and ignition of the fuel [80]) that do not allow it to achieve standard specifications [83] [86] [87]. Blending castor bean biodiesel with diesel is currently the only way to use it in current diesel engines without complicating engine performance while meeting all the required specifications [86] [79]. Castor bean biodiesel's high viscosity could improve diesel lubricity when blended, at a concentration of 2 g/kg, while rapeseed needs to be added at a concentration above 7.5 g/kg to achieve the equivalent effect [13]. Castor bean biodiesel presents a cetane number (CN; 43.7) lower than diesel CN (51). Nevertheless, the B5 blend gave a CN of 50.6 [79]. Moreover, castor bean biodiesel also presents a high cloud and pour point (which monitors the flow proprieties at low temperature [82]), making it suitable for extreme winter temperatures, alone and blended [79] [87]. Castor bean biodiesel requires a negligible amount of catalyst to give a high biodiesel yield, reducing the production cost for large-scale operations [80] [87]. Furthermore, castor bean biodiesel can be obtained at low temperatures [46] [88] for instance, Keera et al. [79] produced castor bean biodiesel through alkaline transesterification, with biodiesel yield obtained at 30°C similar to that obtained at 60°C. It is highly soluble in alcohol, due to the presence of hydroxyl groups, with great advantage during transesterification [13] [81] [88] [89]. A study by Bateni et al. [46] demonstrated that the whole castor bean plant may be used in biodiesel production, with transesterification performed with ethanol obtained by saccharification and fermentation of plant residues; 1 kg of castor bean plant produced 149 g of biodiesel and 30.1 g of ethanol. Meneghetti et al. [90] performed a comparison of ethanolysis versus methanolysis on commercial castor bean oil, obtaining similar yields but a shorter reaction time for methanolysis. All the above-mentioned studies indicate that castor bean is a great feedstock for biodiesel production. Applying a mathematical experimental design and methodology, such as response surface methodology [88] [91] or the Taguchi approach [92] [93], can improve and optimize castor bean oil transesterification. New technological innovations, new diesel engines, and mathematical model applications could greatly increase castor bean biodiesel production and utilization. According to Amouri et al. [94], who studied the impact of castor bean biodiesel production on global warming, energy return-on-energy investment (EROEI), and ecosystem and human health, castor bean biodiesel showed a positive carbon balance, equivalent to a reduction in climate change emissions and an EROEI of 2.60. The above mentioned positive impacts of castor bean biodiesel can also be improved by reducing its indirect land-use change (ILUC); according to Gonzalez-Chavez et al. [62], oil produced by Ricinus shrubs grown on metal-polluted sites presents low levels of contamination (e.g., Cd: 0–1.26 mg/L; Pb: 0–2.2 mg/L) and could be used as a raw material.

Table 2. Comparison of the most common biodiesel feedstocks.

Feedstock	Seed oil Content	Advantages	Disadvantages	References
Castor bean oil	45–55%	Nonedible, high flash point. high pour and cloud point (useful in winter condition), can grow on marginal and PTEs contaminated soils, miscible in alcohol, easily undergoes transesterification	Low cetane number, high viscosity, ricin content	[46] [79] [81] [82] [83] [89] [95] [96] [97] [98] [99]
Soybean	15–20%	Low viscosity, high thermal stability	High production cost, edible, high acid value	[81] [82] [83] [89] [95] [98] [99]
Sunflower	25–35%	Low viscosity	Edible, high acid value, long-term cultivation unsustainable	[81] [82] [83] [89] [95] [100]

Palm	18–40%	Cheap feedstock, high flashpoint	High cloud point, edible, long-term cultivation unsustainable	[81] [82] [83] [89] [95] [101]
Mustard	28–32%	High cetane number, cheap feedstock, can grow on soils contaminated with PTEs	High viscosity, low heating value, high cloud point	[82] [83] [89] [102] [103] [104] [105]
Rapeseed	38–46%	High flash point and low cloud point	Effective power and torque decrease at all engine loads, increased NO_x emissions up to 15% in most experiments	[82] [83] [89] [95] [106] [107]

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