A re-evaluation of castor (*Ricinus communis* L.) as a crop plant

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Abstract

Castor (*Ricinus communis* L.) has been transformed from a wasteland colonizer to an important industrial oilseed crop. Its seed oil is one of the most sought-after vegetable oils because of its rich properties and variety of end-users. Castor is an ancient crop but its production now has been limited mainly to India, China and Brazil, for many reasons. Castor oil is a hot market commodity product. It has been recently recognized as an efficient feedstock for biodiesel production. Increasing demand world over for biofuel resources and many recently identified industrial uses of castor oil have escalated castor oil demand. Global demand for castor oil is rising constantly at 3–5% per annum. In the last decade, many countries have started making serious exploratory efforts at growing castor as there is a tremendous scope to establish castor as a supplementary crop production option to farmers and to provide significant returns on investment given high global demand for castor oil. In view of the increasing worldwide interest in castor oil, this review evaluates the global scenario of castor cultivation, exports and imports of castor oil, new interests in castor oil and genetic improvement in productivity. In addition, the current research challenges and priorities have been discussed in the review.

Keywords: Castor, Drought, Hybrids, Ricinoleic acid, Ricin, Salinity

Introduction

Castor (*Ricinus communis* L.) grows abundant in nature in tropical and sub-tropical countries. It is ecologically recognized as a wasteland colonizer plant, but gained the biological resource status and economic importance because of its seed oil, which is a vital industrial raw material. Castor is among the plants with the highest oil yield potential. Its seed contains approximately 48% oil. Castor oil is a hot market commodity product. Its cultivation assumed great dimensions in the 19th century in India, the UK, the former USSR and the USA as an industrial oilseed crop especially as a lubricating agent, but later interest has gradually diminished, especially in USA, because of many factors. However, in the last decade, interest in castor cultivation has escalated because the industry and consumer have recognized the immense potential of castor oil to meet the demand of growth. Therefore, the promotion of cultivation of castor has become a strategic choice in many countries. In the past few years alone, a number of countries which have cultivated castor a little or had no land under castor have now started making serious exploratory efforts at growing castor. Demand for castor oil in the world is rising constantly at 3–5% per annum (http://www.castoroil.in).

Research into high-yielding cultivars of castor has had a positive impact on crop production and productivity. There are also cutting-edge research efforts being handled by a number of companies on the use of castor to produce bioplastics and biopolymers. However, the research and development efforts in castor are still inadequate for the market to capture the high demand for growth, owing to newer and diverse application of castor oil. Updates and insights on global castor growing and renewed interests, and current status of research are needed for accelerated cultivation, research and commercial efforts. Therefore, the goal of this review was to re-evaluate the global scenario of castor growing, provide a reflection of castor genetic crop improvement, challenges and intensity of efforts in specific areas of research and determine the direction of research considering the global scenario of castor crop.

Brief History

Castor has been known to mankind from time immemorial [1–3]. There are varied opinions about the site of origin of castor. The Ethiopian-East African region is considered to be the most probable site of origin because of presence of high diversity in Ethiopia [3, 4]. Castor is often found as a colonizing plant on wastelands, roadsides, railway tracks, garbage dumps, riversides, etc.

Wild castor was known to be cultivated during ancient periods in Gangetic Plains and South Arabia [3]. In ancient times, wild castor seed were collected for domestic use, later castor was cultivated in settled farming and oasis. The initial breeding efforts in USSR and USA have resulted into development of improved varieties, which have further increased seed yield, oil content and resistance to diseases. Castor oil as an item of trade goes back to ancient times. Castor was in production in USA as early as the mid-1850s and there were over 23 crushing mills reportedly operational at that time. Castor oil trade began to decline between 1850 and 1870 and there were only six mills remained operational in 1870 [5]. In the USSR, castor cultivation started in 1921 and by 1940, the area under castor cultivation had expanded to 229 000 ha with a production of 98 000 tonnes (t). Such a high expansion could be achieved through development of scientific research and organized seed production [3].

World Castor Area

Cultivation of castor is mainly confined to countries lying between the 40°N and 40°S latitudes, but a few cultivars have been found growing and producing seed even up to 52°N latitude in Russia. Castor is produced on a commercial scale in more than 30 countries. World castor area has increased from 1 233 344 ha in 1961 to 1 689 335 ha in 2012 with a peak at 1 994 334 ha in 2011 [Figure 1] (www.faostat.com, accessed on 22 May 2014). India has a 66% share of the world castor area in 2012, an increase from 39% in 1961. China is next (11%), while Brazil was close to India in castor area until 1986 but now accounts for 5%, because of the move away from castor cultivation to soybean (*Glycine max*). Castor is also grown to a limited extent in Thailand, Kenya, South Africa, Vietnam, Madagascar, Ethiopia, Paraguay, Indonesia, Tanzania, etc. Since the late 1970s and early 1980s most countries in the world have gradually decreased or withdrawn from castor cultivation. In contrast, India has expanded castor cultivation from 486 thousand ha in 1961 to 1120 thousand ha in 2012 with 130% expansion in castor area, especially in Gujarat and to some extent in Rajasthan and Andhra Pradesh.

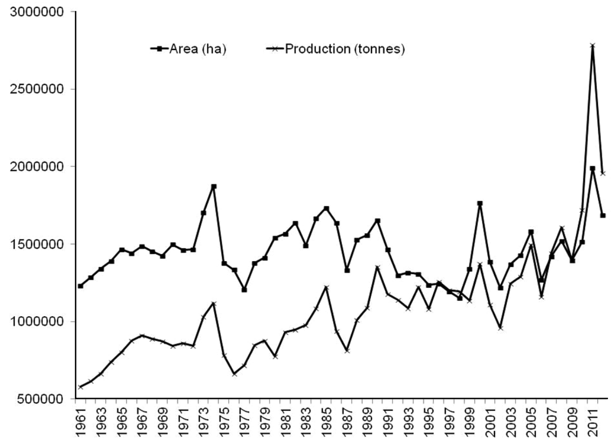

Figure 1. World castor area and production.

World Production of Castor Seed, Oil and Productivity

World castor seed production increased from 580 thousand tonnes in 1961 to 1959 tonnes in 2012 (www.faostat.com), representing a compound growth rate of 1.66% since 1961 [Figure 1]. India produced 83.2% (1630 thousand tonnes) in 2012 (www.seaofindia.com), growing from 18.8% in 1961. Gujarat accounts for 86% of India's production, followed by Andhra Pradesh and Rajasthan. China has 12.5%, and Brazil 5.56%. China, which increased castor production from 35 thousand tonnes in 1961 to 250 thousand tonnes in 2004, moved away from castor cultivation after 2004 to soybean with the current castor production of 180 thousand tonnes.

The world castor productivity has increased 146% in the last five decades with 4.0% compound growth rate in the last decade. The tremendous improvement in castor productivity was mainly because of development of number of high-yielding hybrids, especially in India. The development and popularization of castor hybrids made rapid increase in productive and production in India. Prior to cultivation of castor hybrids, castor production was less than 300 kg/ha, which has now escalated to 1842 kg/ha in 2011. In Brazil, seed yields average around 667 kg/ha over the last 10 years, yield of up to 1600 kg/ha under better soil fertility and agronomic practices [6].

Castor oil is becoming one of the most sought-after vegetable oils because of its rich properties and variety of end-users. The world castor oil production during 2003–2013 has increased from 425 thousand tonnes to current 681 thousand tonnes, displaying 4.82% annual growth rate (www.seaofindia.com). India provided 81.63% (556 thousand tonnes) of world castor oil production in 2013, compared to 11.25% (77 thousand tonnes) share for China and 2.32% (16 thousand tonnes) for Brazil.

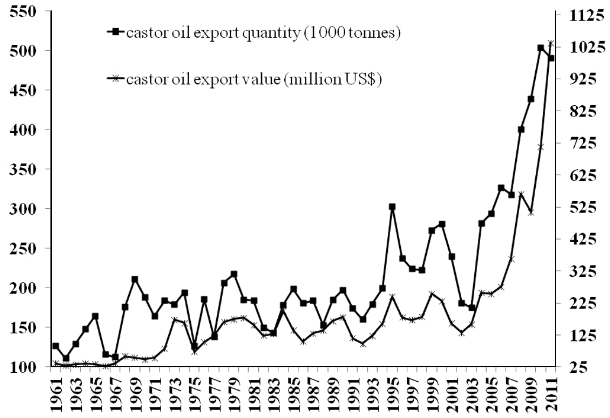

Figure 2. World castor oil export quantity and value.

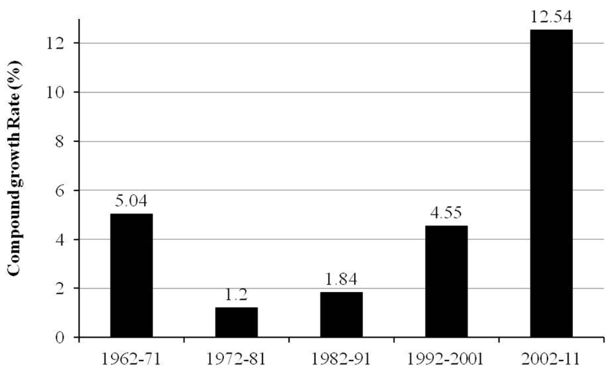

Figure 3. Compound growth rate of world castor oil exports in the last five decades (1962–2011).

World Exports and Imports of Castor Oil and its Derivatives

The world export of castor oil from prominent countries has increased by 3.86-fold from 126 912 t in 1961 to 490 918 t in 2011 with increased export value from US$ 36.16 million in 1961 to US$ 1037.37 million in 2011 [Figure 2]. The world castor oil exports displayed the highest compound growth rate of 12.54% in the last decade (2002–2011) in the history of castor [Figure 3]. India is the biggest exporter of castor oil at 82.75% share of the international trade in this commodity. It has exported 406 244 t of castor oil worth of US$ 834.75 million in 2011 (www.faostat.com). Indian castor oil exports during 2012–13 (April–March castor seed oil year) stood at 430 thousand tonnes (www.inditrade.com). It is expected to be 530 thousand tonnes to 580 thousand tonnes in 2014.

Brazil exported the largest quantity of castor seed till 1980, contributing to 61–71% share in the world castor exports. Brazil has now almost vanished from the global export market, with exports of just 10 627 t in 2011 as compared to 112 966 t in 1980. The compound growth of castor oil exports from India was 11.13% during 2002–2011 with a near 83% share. In spite of being the largest castor oil exporter, so far India is able to capture only about 25% of the total value from the market because of low value addition by the Indian castor oil industry (www.castoroil.in). Exports from China have reduced drastically as it is now a net importer of castor oil. The USA exported 8341 t and EU-27 exported 3071 t in 2011. The other countries exporting castor oil are Ethiopia, Egypt, Ecuador, Madagascar, Mexico, Paraguay, Russian Federation, South Africa, Philippines, Pakistan, Indonesia, Colombia, Argentina, Thailand and UK.

World castor oil imports have increased drastically from 1995 onwards. Currently it stands at 468 419 t worth of US$ 1 063 412 000. The year 2010 was the highest importing (511 783 t) year in castor oil trade sector. The USA was the largest importer and consumer of castor oil in the world barring the EU-27 till 1986. Among EU-27 countries, France, Germany and the Netherlands are the major castor oil importing countries together accounting for 32.17% of the total world imports. China has emerged as a key player in global castor market as a large buyer rather than seller. It is the second largest importer, sharing 30.82% following 30.95% share of EU-27 in 2011. Chinese imports have increased drastically just from 87 t in 1961 to 144 358 t in 2011 (www.faostat.com), representing a compound growth rate of 34.8% over a decade. China's demand for castor oil for domestic industrial applications would continue to increase in future as it is giving more focus on export of sebacic acid and castor derivatives rather than on castor oil export. USA is in third position with 10.52% share. Customers world over have been importing castor oil at a value of around US$2300–2500/t with profits between US$7000–12 500/t.

The major export oriented commodities of castor are castor seed meal, dehydrated castor oil, hydrogenated castor oil, 12-hydroxy stearic acid, and sebacic acid. Global supplies and markets of castor oil and its derivatives are influenced by Indian production. Meal is the byproduct of castor oil extraction. India is the major exporter of castor meal; its meal exports have doubled in last 8 years and touched a record high of 412 thousand tonnes during April–December 2013–14 [Figure 4]. South Korea buys more than 90% of total castor seed meals exported from India (www.seaofindia.com). Sebacic acid is an advanced derivative of castor oil. It is mainly used in production of nylon, plastics additives, adhesives and aviation lubricant. China, the biggest importer of castor oil from India, uses most of the oil for manufacturing of sebacic acid, and exports most of the production to Europe and the USA. It exported 39 689 t of sebacic acid in 2012. Export price of sebacic acid has rallied from US$ 2400/t in 2004 to US$ 5200/t in 2011. The consumption of sebacic acid will increase as new usages of this derivative are being developed [7]. The demand-supply of various grades of castor oil and derivatives is estimated to increase many-fold.

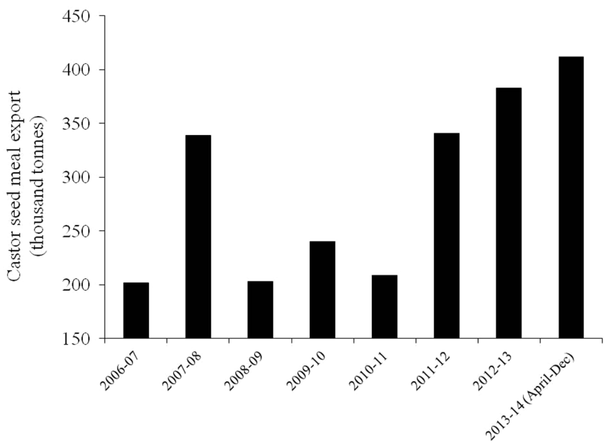

Figure 4. Castor seed meal export from India from 2006–07 to 2013–14 (April–December).

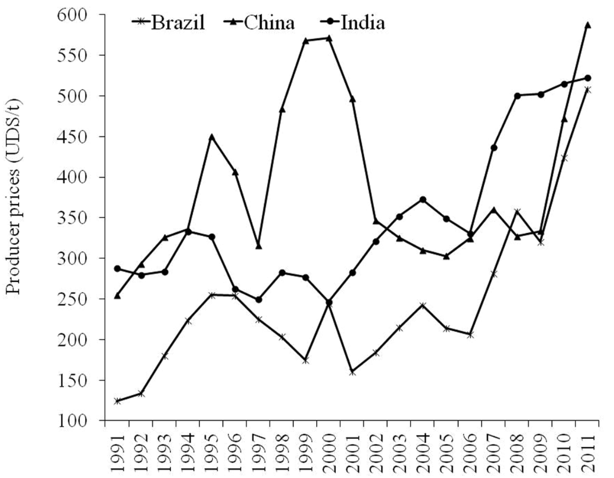

Figure 5. Castor producer price in India, China and Brazil from 1991 to 2011.

Producer Prices

Producer prices (received by farmers) of castor seed have increased in most of the castor growing countries since 2008. The prices have almost doubled in the last two decades in the major castor-growing countries, India, China and Brazil [Figure 5]. Mexico, though producing very little quantity of castor seed from a limited area, recorded the highest producer prices from 1994 to 2011 (US$ 531.2–874.6). The increasing trend of producer price would encourage more castor production in future, if the governments of different countries ensure the remunerative prices to castor-growing farmers.

Castor Oil Price: Trend and Risk

Castor oil is one of the most expensive vegetable oils in the international market. The supply and price of castor oil and its derivatives are highly fluctuating because of fluctuations in production and speculation. The profit margin of higher generation castor derivatives is about 20–50% higher than the basic oil grades. The global castor market is highly dependent on India as it is the dominant player. India has virtually emerged as a price setter in castor oil market and has successfully exploited its monopoly in castor oil production. Castor seed is among the most traded commodities on India's largest farm futures trading platform. Castor seed in India was trading at Rs.15 000–16 000/t in 2005 (around US$ 344–366), and then the price started moving upward in mid-2006 from Rs.16 000/t levels and continued for nearly 5 years. It touched an all-time high of Rs. 61 500/t (around US$ 1361) levels in February 2011. A fall in production during 2009–10 and normal production in 2010–11 pushed up prices to record highs. Despite robust growth in export of castor seed meal and oil from India in 2011 and 2012, prices fell on record output in 2011–12. The castor prices started rallying again in 2013 with 21% rise from Rs 37 310 a tonne (around US$ 673) on 1 January 2013 to Rs 45 120 (around US$ 814) on 31 December 2013. Castor seed prices shot up mainly because of high exports. The average price of commercial grade castor oil in FOB, Mumbai, India has risen from US$ 625/t in 2002 to US$ 1832/t in 2011 and the price of castor seed was US$ 1069/t with an average of US$ 900 (www.castoroil.in; accessed on 23 May 2014).

In India, castor seed prices remain mostly stable or weak during the peak arrival season that is February–June period and touch peak between August and December, which is the lean season. However, the price movement is largely influenced by crop output estimates. The other factors influencing prices are rainfall, prices of substitute oils, domestic and export demand, seasonal factors, stock availability and development of new uses of the oil. The supply and price instabilities impact cash flow, make corporate planning difficult, and discourage research and investment in castor products (www.icoa.org). Castor farmers, producers of castor oil derivatives, and consumers have a critical need to factor in this price volatility in their business modelling and planning. It is imperative to introduce a hedging mechanism for efficient price discovery to minimize price fluctuation (www.castoroil.in).

Renewed uses of Castor Oil

Most of the global castor is credited with 48% oil content out of which 42% could be extracted. Castor oil is one of the most versatile plant oils: it is distinguished by its high content of ricinoleic acid (>85%). The uses of castor oil have changed over the years. In ancient times, castor oil was used for lamp oil and medicinal purposes and later as a general industrial lubricant. Today, there are many uses of castor oil and its derivatives. Owing to its unique chemical structure, castor is used widely in the industrial bio-chemical sector. It can be used as the starting material for producing a wide range of end-products such as biodiesel, lubricants and greases, coatings, soaps and detergents, surfactants, oleo chemicals, etc. [8]. Castor oil has been recognized worldwide as an important renewable energy resource with 500 to 1000 L/ac biodiesel production [9]. Biodiesel derived from castor oil rates high among other oils but its viscosity is much higher than petrodiesel. However, this major bottleneck can be considerably reduced by transesterification making it a very efficient source of biodiesel [8]. Internationally there is increasing interest in the use of castor as biofuel feedstock mainly because it is a non-food crop and its exploitation would reduce consumption of edible oils for biofuel production thus can reduce food crisis expecting to arise due to consumption of edible oils in biodiesel production.

Besides the major castor growing countries in the world, many countries especially from South East Asia, Africa and South America are showing significant interest in producing castor oil and castor chemicals on a large scale in future. Several global research institutes are looking at castor oil as an alternative source to replace petroleum-based organic chemicals with castor oil biorefinery concept for the preparation of thousands of derivatives [10]. There are several innovative technologies for the production of value-added castor oil chemicals and derivatives. Food-grade castor oil is used in food additives, flavourings, chocolate, as a mould inhibitor and in packaging [11]. The uses of castor oil in industry are plenty and diverse [12]. With new applications of castor oil being discovered, especially in telecommunications, pharmaceuticals and biopolymers/bioplastics, the markets for castor oil and its derivatives are expected to expand extensively in the near future. Castor oil is used either in its crude form, or in the refined hydrogenated form. Typically, 65% of it is processed, of which, about 28% is refined, 12% is hydrogenated, 20% is dehydrated, and the balance 5% is processed to manufacture other derivatives. The major derivatives of castor oil used in the industry are hydrogenated castor oil, dehydrated castor oil, sebacic acid etc. (www.castoroil.in).

The castor plants act as sink for carbon dioxide (CO_2) as castor plants capture around 10 t of CO_2 for every hectare planted, which offers another avenue for revenue in the form of carbon tax credits (http://www.oilseedcrops.org/cator-bean; http://www.jatrophabiodiesel.org). A study in Indian context reported that if 10% of total production of castor seed oil is transesterified into biodiesel, then about 79 782 t of CO_2 emission can be saved on annual basis [13]. The CO_2 released during combustion of biodiesel can be re-cycled through the next crop production cycle, therefore posing no additional burden on environment. Castor can make a large contribution to the world's future biodiesel requirement. The challenge is to harness biodiesel on economically sustainable manner and without causing land use change from food crops and compromising food security. Currently, high price of castor oil in world market is a challenge to make castor-based biofuel economically feasible. However, castor-based biodiesel is expected to be a substantially cheaper alternative than biodiesel developed from crops such as canola, maize and soybeans [14].

Castor Industry

The major end-use industries for castor oil derivatives such as lubricants and greases, coatings, personal care and detergent, surfactants and oleochemicals, showed 2–6% compound growth rate since 2005. Castor-based bio-fuel industry is also growing but significant role of castor oil in biofuel industry is doubtful given the ever increasing high demand for castor-based byproducts, relatively high cost of castor oil and low production of oil. However, in high-growth segments such as pharma ingredients, biopolymers and food ingredients castor oil could be important. It is expected that there will be many more segments within pharma as well as biopolymers and food ingredients in which castor oil can significantly increase its presence (www.castoroil.in).

Public–private partnership gained prominence in recent years. Joint efforts between Governments and industry are being explored in many countries in order to make castor cultivation profitable. There are a few key Indian, Chinese and Brazilian companies involved in castor oil industry. All top five castor oil companies (by volume of oil output) are in India. Presently more than 30 internationally operating wholesalers have joined together in the International Castor Oil Association Inc. (ICOA) founded in 1957, which involves in castor growing, processing, trading, marketing and/or consuming castor oil. The ICOA disseminates the information related to castor production to trade of oil and derivatives to its members and the industries they serve (www.icoa.org). The Solvent Extractors' Association of India (SEA) continuously gives feedback to its members about the developments taking place in the country and world. Nielsen India is the largest market research agency in the Indian subcontinent with the requisite experience, expertise and infrastructure to conduct castor crop estimation study. CastorOil.in (http://www.castoroil.in/) provides comprehensive resources related to castor oil, castor derivatives and castor-based oleochemicals and also provides over 500 web-links to various aspects of castor crop and castor oil. These links and associations may provide information required for formulating programmes on castor-based research and adoption.

Castor Plant and its Growth Requirements

Castor is a diploid ($2n=2x=20$) species belonging to the family Euphorbiaceae and the genus *Ricinus*. Great diversity has been reported in important traits of interest [15].

Castor has a long taproot that can penetrate the soil up to 2–4 m deep. In case castor is grown as perennial, the taproot can even go up to 5–6 m in soil. The lateral roots spread up to 1 m laterally. In case of moisture stress conditions, taproot grows deeper with a little lateral roots spreading. Castor cannot tolerate water logging because of sensitivity of its root to hypoxia caused by soil flooding. Castor root system suffers irreversible damage after just 3 days of flooding [6]. Castor plant is well foliated and great variation exists naturally for leaf size and petiole length. The most common stem colours are green, red and green and red colour mix with varying intensities. The dark purple and sulphur-yellow colour stems are occasional. There are castor plants with or without waxy (bloom) coating.

The castor inflorescence is monoclinous monoecious raceme bearing female flowers near the apex and male flowers proximally. Male flowers do not bloom uniformly, the period of their period is longer as compared to that of female flowers depending upon on the proportion of male to female flowers on a raceme. Castor reproduces by both cross-pollination and self-pollination. Castor has prolonged period of flowering because of its indeterminate growth habit. It keeps growing and reproducing as long as congenial growing conditions are available in the crop season. The primary raceme comes to flowering first; then within 4–5 days the secondary order racemes will flower and within similar intervals of time subsequent order racemes will flower. Cross-pollination occurs primarily though wind [3]. Controlled pollination is necessary in breeding programmes because the pollen can be carried by wind as far as 500 m. Primary raceme is the major yield contributing trait; the contribution of each raceme order to the total seed yield is not a stable trait [16, 17] as it is highly dependent on the growing conditions prevailed during individual raceme growth period. Number of racemes per plant is also an important yield contributing trait but highly dependent on environment. Great variation exists in castor seed colour, size, shape and weight. Castor seed weight as low as 7 g/100 seeds and as high as 86 g/100 seed were reported in castor [18]. Seed is the source of oil in castor plant. Castor grows in the wild as a perennial that bears seeds for about 8–12 years and grows to the size of a small tree. Duration of vegetative growth changes depending up on soil water availability but at the same time it is a genetically controlled trait and has a positive association with number of nodes on main stem and plant height [19]. The factors affecting castor crop are frost, low rainfall and pest and disease attacks.

Castor grows as an indeterminate annual or perennial shrub depending on climate and soil types in tropical, subtropical and warm temperate regions in the world that do not experience frost and snow. Freezing temperatures kill the castor plant and impede seed germination, therefore it grows as an annual crop in temperate regions. Air humidity between 30 and 60% is ideal for castor growth, too high air humidity increase pest and moulds incidence on castor plant. Wild castors plants were found growing from sea level to above 2000 m.a.s.l. [15] but optimal altitude is 300–1800 m.a.s.l.

Ecologically, castor is recognized a good colonizer of wasteland and marginal lands [20]. The ecological significance in terms of productivity and production of organic and inorganic minerals indicates that castor is an ideal plant for restoring disturbed soil and colonization of wasteland [21]. Biomass production of individual plants of castor is higher when compared to other wasteland species such as *Achyranthes aspera*, *Abutilon indicum*, *Cassia occidentalis* and *Withania somnifera* [22]. Castor is considered as an invasive crop in some countries as it interferes with the natural vegetative landscape. Castor is a long-day plant, but is adaptable to a fairly wide photoperiodic range. Daylength of minimum 12 h is required for its normal growth and below it the growth and development will be affected. Castor requires average day temperatures of 20–30 °C with a minimum of 15 °C and a maximum of 38 °C.

Castor is not a food crop and can be grown productively on underutilized marginal uplands unsuitable to grow other food crops. It can survive on various types of soils thus provides an excellent opportunity to utilize land resources more productively. Castor is usually cultivated as an annual crop with a growing period of 5–6 months or even more. It comparatively requires little water and fertilizers but needs an appropriate and consistent rainfall to become an economically viable crop. Castor can be grown in both irrigated and rainfed conditions and on almost all types of soils provided they are fairly deep (45 cm) and well drained. Castor is sensitive to poor drainage, water logging, saline and sodic soils. Heavy clay soils should be avoided for castor cultivation. Castor planting date in a region has to be determined considering soil and day temperature as well soil moisture availability. Planting date in cooler regions should be determined in such a way that the crop would not face frost during its growing season. Castor needs a frost-free period of 140–180 days. Castor grows normally only when there is sufficient soil moisture. Its requirement of rainfall during different growth stages differs but requires a minimum of 300 mm rainfall during its growth. Castor yields as much as 350–650 kg of oil per hectare in arid and semi-arid regions under low-input conditions. It is very sensitive to weed competition especially in early vegetative stage.

Castor has capacity to grow in polluted soils contaminated with toxic heavy metals [23]. It is efficient for phytoremediation of high concentrations of Cd, Zn, manganese (Mn) and lead (Pb) from contaminated soils [24, 25] and also has great potential for removing DDTs from contaminated soils. Genotypic differences in accumulation and translocation of DDTs and Cd have been also reported [23]. A study on metal accumulation in castor growing on spent-lubricating-oil-contaminated soil has showed that Mn, nickel (Ni) and Pb were mostly accumulated in the leaves and vanadium (V) in roots [26]. Castor is also a hyperaccumulator of copper (Cu) and arsenic (As) and a potential candidate plant for phytoremediation of Cu and As contaminated soils [27–29]. Pandey [30] reported castor to be a promising candidate for phytostabilization and revegetation of fly ash disposal sites which are contaminated with heavy metals like Cd, Pb and selenium (Se).

Castor has ability to grow well with wastewater irrigation. Mamta *et al.* [31] have done a comparative study between various types of energy crops for their energy generation under wastewater irrigation. They indicated that castor grown using wastewater could give high energy yields (196×103 MJ/ha) and helped in phytoremediation of soil. Oladoja *et al.* [32] reported that the shell of castor seed could serve as a sorbent in the treatment of basic dye contaminated wastewater. Vanaja *et al.* [33] recognized the ability of castor to grow under increased concentrations of CO_2 in atmosphere, suggesting its potential under changing climatic conditions.

Early Challenges in Castor Yield Improvement

Castor breeding initially was not as intensive as in food crops or other commercial oilseed crops. There were a few documented reports on historical efforts on castor breeding. There is no temporal gap between uncultivated and cultivated castor. Wild castor collections date to many centuries. These were cultivated during ancient times and were gradually transitioned into cultivated forms initially through conscious selection for desirable types. The initial constraints in improving castor were its seed shattering (dehiscent) nature, late duration and low yield, frost and drought susceptibility, indeterminate growth habit and susceptibility to large number of insects and diseases. The genetic resources available to castor breeders represent a rich repository of genetic variation, which formed the basis for castor breeding progress. Recorded history of castor collection and distribution can be traced to early taxonomists and botanists from former USSR between 1773 and 1976. All-Russia Research Institute of Oil Crops (VNIIMK), N.I. Vavilov Institute of Plant Industry (VIR) and Botanical Institute of the Academy of Science of the USSR (BIN) are the oldest institutes which began collecting castor genetic resources in 19th century. A number of research efforts have been initiated towards the development of varieties in USSR and USA by exploiting natural variation in this crop.

The former USSR made great initial efforts to convert castor wild strains into commercial varieties. The basic traits on which castor breeding had concentrated were *per se* seed yield, short duration, low number of main stem nodes, long productive primary and secondary racemes, high number capsules on a raceme, high seed weight, high oil, resistance to major diseases. Besides these, a number of other traits such as stem colour, bloom on leaf, non-spiny nature of capsules and low percentage of unfilled seeds, suitability to mechanized harvesting and high oil yield were also taken into account. The productive wild forms with a female type of flowering or those inclined towards female type racemes have played a major role in increasing castor productivity in breeding programmes. Initial materials were improved by direct selection and hybridization among geographically distinct wild collections. Inbreeding was also practiced to isolate recessive type traits such as indehiscent capsules, non-spiny and dwarf type. Simultaneously, breeders have established the major yield contributing traits and their inheritance and correlations with yield and duration and other traits. Breeding methods used in castor improvement programmes have been detailed by Kulkarni and Ramamurthy [2].

Variety Improvement

Historically, castor varieties were developed during 1922–1939 in USSR through mass selection and hybridization. Tashentskaya 351 was the first non-dehiscent type variety in the former USSR, and VNIIMK 165, early hybrid, Kavakazskay, Kruglik 5, Stepanaya 6 and Donskaya 172/1 were the initial early maturing varieties developed from hybridization among wild selections. An early maturing variety Shade was derived from a cross between Persian and Chinese collections. The high oil varieties, Sanguineus 401 and Sanguineus Synthetic were developed through inbreeding of germplasm accessions. Two varieties from China (Kuha bi Bao, Fu gun'er), the Australian variety, Ceripi Wild and the Hungarian variety, Iregi were derived from germplasm. These varieties were less productive, susceptibility to *Fusarium* wilt, very tall, more branching, long-duration forms and less suitable for combine harvesting. The variety Chervonnaya was the first *Fusarium*-wilt-resistant castor variety in which wilt resistance was introgressed from small-seeded *sanguineus* castor [3].

Since 1959, attention has been paid to developing high-yielding varieties suitable for combine harvesting, with resistance to the major soil-borne disease, *Fusarium* wilt. Development of dwarf internode cultivars, Dawn, Hale and Lynn, in USA has significantly enhanced seed yields in castor [34–36]. However, withdrawal of government price support in 1972 led to very limited research in USA. Though USA does not currently commercially produce castor, it has been reported that yields of irrigated castor from Texas range from 2242 to 3363 kg/ha [37], indicating potential for high yields in USA. American dwarf varieties, Baker 296, Dawan, Hale, Lynn and Campinas were widespread in Brazil, Equador, Sudan, Kenya, Uganda and Thailand. Under irrigated conditions these could yield up to 3000 kg/ha. In France, dwarf varieties such as Frantsiya and 301 M were introduced. A collaborative breeding programme including Germany, Italy, Portugal, Greece and France was initiated in France in 1991 for castor breeding and crop management [38]. In Brazil, the genetic improvement of castor started in 1936. The local Brazilian varieties were of long duration and indeterminate growth habit type which yield around 600 kg/ha. A dwarf variety, IAC-38 and the varieties *viz.,* Guarani, IAC-80, IAC-226, BRS Energia and IVA-2028 were developed in Brazil [39]. China too developed several high-yielding cultivars namely, Zixuan 308, Honggan No. 1, Hongta No. 2, Lifen No. 3 and Huangzhuan No. 6. The last two are ornamental type with pink and yellow colour capsules and come to flowering in 30–40 days after emergence and the other three are early maturing type, which take 100–115 days for primary raceme maturity.

In India, castor variety improvement programme has gained movement between 1920–1930 with the development of high-yielding varieties, HS-6 and HC-7. These were non-shattering, multiple branching, very late maturing (220–270 days) and high oil-type varieties and became popular among farmers. The initial breeding efforts could increase yield by 10–20% and oil content by 1–2% over the local varieties. The breakthrough came in late 1960s with release of a short duration (110–150 days) variety, 'Aruna'. It was developed from the very long duration variety, HC-6 (220–280 days) through thermal neutron mutagenesis. The alteration of several morphological features of HC-6 through mutation breeding facilitated 'Aruna' variety to be more responsive to intensive management practices. Subsequently another short-duration variety, 'Bhagya' and a convergent dwarf plant type variety, 'Sowbhagya', suitable for intercropping system were released in 1974. More than 50% yield improvement over HC-6 could be realized from 'Aruna' and 'Bhagya' in the short duration (5 months) crop period. These varieties were found most suitable to Andhra Pradesh State. The tall late variety S-20 was cultivated until 1970 in Gujarat, the major castor-growing State, and later a short duration variety GAUC-1 (VI-9), a selection from S-20, was developed, which was highly susceptible to *Fusarium* wilt. In Tamil Nadu, the late maturing varieties Co-1 and TMV series 1–3 were introduced initially and later these were replaced with relatively earlier type varieties, SA-1, SA-2 and TMV-5. The variety, RC-8 was released for cultivation in Karnataka and the very late maturing and bold seeded varieties, Kalpi-6 and T-3 were released for cultivation in Uttar Pradesh. The most significant achievement in variety improvement programme in India was development of *Fusarium* wilt-resistant high-yielding varieties such as 48–1, 'Haritha', 'Jyothi' and GC-3. These varieties could yield 1000–1500 kg/ha under dry conditions and the varieties 48-1 and GC3 could yield more than 2000 kg/ha under irrigated conditions.

Hybrid Castor Success

White [40] first time discovered that the hybrids produced by crossing different castor types often showed increased seed yield, when compared to parents. Later on, several studies reported great extent of heterosis for seed yield and yield contributing traits [41, 42]. Absence of marked inbreeding depression was also presumed in castor. Developing hybrids to capitalize heterosis started with identification of plants having racemes having only female flowers. Great variation exists in proportion of male to female flowers on a raceme. Several sex variants such as plants having racemes with only pistillate flowers, with only male flowers and with various proportions of pistillate and staminate flowers interspersed along the entire length of raceme exist in castor [43–47]. In the former USSR, a selection, K-57, from a local population of Crimea had produced 50% of female plants and was found suitable for hybrid seed production without emasculation. Test hybrids produced using K-57 had yielded 2.6 times higher than the most productive parental lines. These hybrids were also early maturing by 8–10 days. Selection of pistillate plants from germplasm collections has started in USA at the end of 1930s. Nebraska 145-4, identified in a natural population, was the first stable pistillate line in castor. It was a female parent of commercial hybrids in USA. The US hybrids, Baker 22, 23, 44, 55 and 66 have acquired wide acceptance in Brazil and several African countries. Nebraska 145-4 is an N-type pistillate line. In this type, reversion to monoeciousness is late and nearly 50% of plants will remain female. The expression of pistillate character in Nebraska 145-4 is controlled by one major recessive gene and appeared to be influenced by modifying factors and environmental conditions [48]. For the production of F_1 hybrid seed using N-type pistillate line, the producer has to rogue out normal monoecious plants before anthesis. This was difficult to achieve in practice because of uneven emergence of male flowers, variation in time of flowering and higher percentage of monoecious plants than expected 50%. Despite these problems, commercial production of hybrid seed in the USAs was mostly with N-pistillate lines. However, subsequent development of S and NES-type pistillate lines substantially reduced the cost of hybrid seed production. S-type pistillate system behaves like a polygenic complex. NES-type pistillate system is recessive homozygous for the pistillate gene (f) and contains environmentally sensitive genes (s) for interspersed staminate flowers [49]. This system was found to be advantageous to the breeders since introgression of a single recessive gene for femaleness is easy to accomplish and the environmentally sensitive genes confer advantages for its maintenance [50].The NES type pistillate line, CNES-1 derived from a VIR collection k-1182 released at Davis, California in 1964 was extensively used in hybrid seed production. A complete femaleness type pistillate line, TSP-10R (Texas S-pistillate 10), was released in USA in 1962.

In India, the major breakthrough in productivity came through exploitation of heterosis. Continuous breeding efforts made under the All-India Coordinated Research Project on Castor have led to release of several high-yielding castor hybrids. Commercial hybrid development in India has started with introduction of a pistillate line, TSP-10R, from Texas in 1965. An indigenous pistillate line, VP-1 derived from TSP-10R and several derivatives of VP-1 have been used as a pistillate line in the released commercial hybrids in India. The first castor hybrid, GCH-3, yielded 124% higher over the varieties under cultivation; however, the seed shattering nature of this hybrid forced pre-mature harvesting. Hence, it was replaced later by a non-shattering hybrid, GAUCH-1. However this hybrid was highly susceptible to *Fusarium* wilt and *Macrophomina* root rot. This has been later replaced by the hybrid, GC2, which was tolerant to root rot to some extent but not to wilt. With the development of GC2, castor cultivation has spread rapidly, owing to high economic returns. Monocropping of castor has resulted into endemic development of *Fusarium* wilt in castor growing areas in Gujarat. This has necessitated the development of *Fusarium*-wilt resistant hybrids in India. The most popular wilt-resistant high-productive hybrid, GCH-4, has replaced GC2. GCH-4 has ruled castor cultivation until recently. Farmers have realized 48–158% increased yield from GCH-4 under both rainfed and irrigated conditions. The GCH-5, a wilt-resistant hybrid, released in 1995 gave 13% more yield than GCH-4. Besides a series of hybrids, GCH-6, GCH-7, DCH-30, DCH-177, DCH-519, YRCH-1 and PCH-111 have been released under All-India Coordinated Project on Castor. Most of these hybrids have capacity to yield around 1500–1600 kg/ha under rainfed conditions and more than 2000 kg/ha under irrigated conditions. All these hybrids are of medium duration (5–6 months) type and resistant to *Fusarium* wilt and possess 48–51% oil content. These hybrids were highly responsive to irrigation and fertilizer. Currently, GCH-7 has taken a dominant place among all Indian castor hybrids because of its very high productivity and wilt resistance. It has increased national average of per hectare yield of castor. It could yield around 1500–1800 kg/ha under rainfed and 3000–3200 kg/ha under irrigated conditions.

Castor hybrids have wider adaptability and stability to perform well under rainfed and irrigated conditions. Castor hybrids in India were introduced for cultivation in 1972 and by 1978 around 98% of total castor acreage in Gujarat came under castor hybrids. As a result, the average castor yield in Gujarat, which was once below world and Brazilian levels, increased continuously and surpassed both of them. The average castor yield in Gujarat stands now more than 2000 kg/ha. Castor has become economically competitive crop to Gujarat farmers because of the high-yielding potential of castor hybrids and the remunerative castor prices in the market. The other advantages which encouraged farmers to take up castor hybrid cultivation were the high income generated by growing hybrids that helped farmers withstand liquidity problems; requirement of less supervision and management time in cultivating castor; capacity of to grow in less fertile soils in which other crops could not do well and less risk involved in growing castor. The already built-in infrastructure of marketing and retailing hybrid seeds by various private seed companies have facilitated the process of adoption and distribution of hybrid seeds to farmers on time and at the reasonable prices. The well-organized and reliable seed multiplication system built up by private firms in which quality was accorded utmost consideration, won the farmer's confidence [51]. Castor productivity has increased tremendously in the last decade with an impressive 3.6% annual compound growth rate in productivity mainly because of adoption of high-yielding hybrids.

The castor planted in China came from India and has a history of more than 1400 years. In China, castor is planted in large regions from southern Hainan Island to northern Heilongjiang province. The major castor-growing areas are Yellow River Valley and Yangtze River valley. Castor cultivation was common in China before the 1980s, but it was given up gradually in many regions because of the low yield of local varieties, low economic benefit, small cultivation area and limited marketing. Zibo Academy of Agricultural Sciences (Zibo Branch of Shandong Academy of Agricultural Sciences) initiated castor hybrid breeding in China. In 1984, a plant without male flowers was discovered for the first time and a series of pistillate lines were developed by inducing of agronomic techniques. Using the pistillate lines, the Zibo Academy has bred several high-yielding castor hybrids, ZiboCastor No. 1 to 9 in progression. The reported yield of these hybrids is between 3200 and 4500 kg/ha with oil content around 51% under wide spacing of 100–120 cm between rows and 70–80 cm within a row. All these hybrids are of late-flowering type with initiation of flowering in primary raceme after 90–120 days after emergence. Most of these hybrids are suitable to grow in the regions in China where frost-free period is 110–145 days. All these hybrids are non-shattering. As per Zibo Academy of Agricultural Sciences, castor hybrids are drought-resistant and salt-tolerant, and are suitable for cultivation in almost all arable lands except waterlogged lowland. The hybrids have been popularized in more than 20 provinces and autonomous regions in China as well as in more than 10 countries such as Indonesia, Malaysia, Pakistan, Laos, Thailand, Vietnam, Ethiopia, Nigeria and Netherlands, etc. (www.castorchina.com).

Current Challenges and Research Priorities

In the last decade many countries and entrepreneurs have recognized the high potential of castor crop. The demand for castor oil is increasing continuously owing to ever-expanding uses of castor oil and its derivatives. This has led to wide demand-supply gap for castor oil. Although hybrids adoption has increased castor productivity tremendously, the potentiality of hybrids is not realized fully across locations, mainly due to cultivation of castor predominantly on marginal and sub-marginal lands, total dependence of yield on seasonal rainfall and its distribution, and input starved conditions coupled with poor crop management by majority of small and marginal farmers. Use of varietal mixers or long duration varieties, and similar cultivation practices for all growing regions or age-old cultivation practices have also contributed to some extent for low productivity of castor.

A much higher research thrust on productivity improvement is needed for mitigating the demand-supply gap. Besides, the breeding efforts should focus on three other prime objectives: (1) improvement of oil quantity and quality, (2) development of toxin-free castor and (3) selection and breeding needed for adoption of castor crop to drought, salinity and cold temperatures or frost. The optimum agro-ecological conditions have to be determined to realize and sustain higher production potential of newer genotypes. Quality seed supply of available high yielding region-specific cultivars should be a priority.

Enhancement of castor productivity: Improved crop management and better varieties and hybrids are largely responsible for the productivity increase in the past decades. However, low yields and limited economic returns are still limiting factors for adopting castor crop in many countries. Increase in crop productivity depends on different bio-physical and socio-economic factors. Castor crop in arid and semi-arid regions is often cultivated in marginal or sub-marginal lands, which are not profitable to grow other crops because of one or more problems that reduce crop productivity. These problems can include drought, nutrient imbalance, pH imbalance, frost, heat, region-specific pests and diseases. These are often not addressed while adapting the crop, hence, realization of actual productivity potential of crop remains difficult. These problems need to be addressed via developing climate-adapted high-yielding castor cultivars. Intensive research efforts are indeed needed in understanding the important environmental constraints to productivity especially in marginal lands and castor plant requirements for adaptation to the identified constraints. Limited vegetative growth, determinate growth, nutrient and water stress tolerance and salinity tolerance are obligatory research topics for production of castor in arid and semi-arid environment.

Suitable breeding strategies targeting exploitation of the genetic variation for yield and its traits in the target environments for productivity improvement should be designed. Breeding in real sites that individually represent the important stress factors in marginal lands over space and time may improve productivity. Castor breeding should primarily focus on exploitation of vast germplasm available in castor for discovering new genes and gene combinations to meet the newer requirements. Unfortunately, germplasm exchange among different countries has become a sensitive issue under the present international treaties. Therefore, previously exchanged material and native collections should be thoroughly searched for traits of research interest. Targeted utilization of germplasm and synthesis of target-based populations and heterotic pools are needed for rapid improvement in important characteristics. The countries interested in castor research and cultivation should provide financial support to researchers for unravelling the great potential of available genetic resources.

An information feedback mechanism from farmers to breeders should be developed to overcome the shortfalls in crop management technologies and cultivars. Intervention of both improved varieties/hybrids and agronomic practices are needed to enhance productivity, especially in marginal lands. In India, introduction of improved castor varieties/hybrids could improve castor productivity by 11–115%, timely fertilizer application by 12–69% and plant protection measures by 23–45%. With adoption of currently available castor production technology, farmers in India could realize an additional yield of 8–150% over the prevailing farmers' practices under a wide range of agro-ecological and crop growing situations [52].

Low soil fertility is one of the most important factors constraining castor yields in marginal and sub-marginal lands especially in arid and semi-arid regions. There is an absolute requirement to maximize nutrient use efficiency using both agronomic and plant breeding approaches. The soil fertility condition can be improved by incorporating fertilizers but it is not economically feasible for poor farmers. Nutrient-efficient castor cultivars possessing high nutrient uptake and utilization efficiency offer an alternative to solve the problem. Nutrient-efficient genotypes would have the ability to produce a higher yield than non-nutrient efficient genotypes in a soil that is deficient in one or more mineral nutrients. Firstly, the response of castor plants to nutrient deficiency stress should be understood, and secondly, genetic diversity for nutrient use efficiency should be explored. Nutrient use efficiency in castor is not well studied; therefore, selection for nutrient-efficient genotypes should be based on yield performance in a nutrient-limited environment. However, a holistic approach combining root characteristics to enhance acquisition, canopy, seed filling and yield in target environment would be a better approach in determining an efficient selection method. Information of other agronomic characters related to yield in target environment would be beneficial for plant breeders as selection criteria in developing nutrient-efficient castor genotypes. Understanding of inheritance of nutrient use efficient traits is valuable in breeding for these traits. The physiological processes contributing to the overall nutrient use efficiency under stress condition should be identified. Multidisciplinary approaches are needed to develop nutrient-efficient cultivars. The mechanism of uptake and use-efficiency of each nutrient must be analysed separately and the yield performance should be studied across nutrients as nutrient interactions influence seed yield.

Plant genetic engineering has become one of the most important molecular tools in the modern molecular breeding of crops. Experimental transgenic castors have been reported [53] but very low transformation frequency is still a problem in castor transgenic experiments [54]. The recent completion of the castor genome may provide an opportunity to have an insight into molecular mechanism of different yield contributing traits. One can also think of development of introgression libraries and their molecular-genetic characterization to localize genomic regions carrying favourable alleles affecting *per se* performance of desirable traits. Xu *et al.* [55] made an extensive search of castor genome and identified putative 114 AP2/ERF family genes, which play a crucial role in the regulation of growth and development, metabolism, and responses to biotic and abiotic stresses. Computational analysis of the castor genome database has identified 15 candidates of the SBP-box (SQUAMOSA promoter-binding-protein) gene family, which encode transcriptional regulators and perform a variety of regulatory functions that involve in the developmental and physiological processes of plants [56]. This analysis has provided strong supporting evidence for the evolutionary diversity of SPL genes in the castor.

The use of molecular-marker-assisted breeding is clearly a feasible alternative to genetic engineering technology, particularly given the public concern over the use of genetically modified (GM) crops. Lack of genomic resources has hampered the application of marker-assisted breeding in castor improvement. High-density molecular maps, the necessary framework of molecular-marker-assisted breeding, are yet to be constructed in castor. Detailed molecular studies integrated with quality phenotyping would help castor breeders in identifying the appropriate parents to include in breeding crosses, assignment of genotypes to appropriate heterotic groups, and major alleles that will enhance selection for complex traits. The techniques and knowledge required for molecular studies are usually not available to many castor breeders. A new generation of breeders with education and training in molecular breeding are needed to employ a molecular breeding approach. If the high price tag that comes with molecular tools is reduced, the benefits of application of molecular breeding approach in castor would increase many-fold.

Interspecific gene transfer is an important tool for crop improvement. However, as castor is a monospecific species, there is no opportunity for alien gene transfer into its genome. Recently, there was a report on intergeneric hybridization of castor ($2n=2x=20$) with cassava (*Manihot esculenta* Crantz; $2n=2x=36$), the other cultivated member of the Euphorbiaceae family with an aim to bring novel traits of commercial value from castor to cassava [57]. This attempt may give an opportunity to derive male-sterile stocks in both the crops resulting from incomplete or unstable pairing of chromosomes. The male-sterile lines, if developed, would replace environmentally influenced pistillate lines in castor hybrid seed production. In the event of complete elimination of cassava chromosomes, there will be an opportunity to derive castor haploids and then double haploids following chromosomal doubling.

Using a biotechnology technique called Clean Genome Multiplication (CGM), Kaiima Bio-Agritech could create polyploidy in castor and other crops, without encroaching on DNA. In addition to increasing yield, this company also claims improvement in crop's tolerance to biotic and abiotic stresses, improvement in land and water-use efficiencies and increase in CO_2 fixation using this technique. The company claimed development of a polyploidy castor yielding 10 t/ha using CGM technique (www.israel21c.org). However, for acceptance of this claim by castor researchers and producers a thorough validation of polyploidy castor is further needed.

Need for High Oil Producing Castor

Castor is among the plants with the highest oil yield potential. The genetic improvement efforts have increased the oil content of castor from 24 to 48%. Castor oil is in high demand as a renewable feedstock for production of biodiesel. Castor oil biodiesel has several advantages over other vegetable oils due to low levels of residual P and C, absence of aromatic hydrocarbons, high cetane number and high quality, solubility in alcohol and does not require heat in transforming into fuel (Ogunniyi [12]). The castor oil-based products can have lower environmental impacts and higher degradability than petroleum-derived products, and can deliver higher returns for castor farmers. Considering the high demand for castor oil, the major research thrust should be on enhancement of castor seed oil content and oil yield. Currently the released cultivars contain 48–51% seed oil content. Wild accessions with 56–59% oil content are available in the existing germplasm collections of many countries [58–60]. These can serve as base material to breed high-oil cultivars through traditional breeding methods. Oil content is a polygenic control trait based on numerous contributing factors [61–63], and heterosis exists for oil content in castor [64, 65]. Castor oil is endosperm oil; the kernel oil content is around 64–75% [66]. Oil content of the seed is not much influenced either by planting time or by different moisture regimes [67] but location effect on oil has been reported [68]. Castor hull occupies 25–30% of the seed. There is a negative correlation between hull and oil content. Both the traits are under polygenetic control and show large variation [61, 69]. Variability exists in germplasm for hull content; this suggests possibility of improving castor for increased oil content in endosperm by reducing hull content. Seed oil QTL identification, understanding the molecular mechanism of seed oil accumulation, and genetic modification may help in enhancing oil content. The castor genome sequence and its annotation would help identifying the regulatory and metabolic networks controlling castor oil biosynthesis [70]. Based on the castor genome, an extensive search was performed to identify potential AP2/ERF transcription factors involved in oil accumulation or seed development of castor [55]. It was found that the gene 30069.m000440 may be a potentially important transcription factor responsible for regulating oil accumulation in developing seeds of castor. Further studies on the functional analysis of this gene are needed to reveal the mechanism underlying the regulation of oil accumulation in developing seeds of castor. Kim *et al.* [71] reported the identification of *LEC2* (*LEAFY COTYLEDON2*) gene that exists as a single-copy gene in castor and is expressed predominantly in embryos. Expression of castor *LEC2* in *Arabidopsis* increased the expression of fatty acid elongase 1 (FAE1) and induced the accumulation of triacylglycerols, especially those containing the seed-specific fatty acid, eicosenoic acid ($20:1^{\Delta 11}$), in vegetative tissues.

Oil Quality Improvement and Alteration

Castor oil is unique among all fats and oils. It is the only source of ricinoleic acid (ricinoleate; 18:1-OH), which comprises approximately 85–87% of the fatty acid composition in castor oil. Ricinoleic acid is considered safe and non-toxic. It is a monounsaturated 18-carbon fatty acid with a hydroxyl functional group at 12-carbon. Double bond and hydroxy functionality along with carboxyl group projects this oil as an extra-ordinary source for preparation of thousands of derivatives. Over 50 000 t of ricinoleic acid sourced from castor is used annually for the production of N-11, a highly desirable polymer for the manufacture of tubes used to carry hydraulic fluids in automotive engines. More lipophilic form of ricinoleic acid can be used as an analytical source for biodiesel production [72]. Any further increase in the level of ricinoleic acid would be beneficial to industry. Great diversity exists in castor germplasm for ricinoleic acid content percentage. Bhardwaj *et al.* [73] observed 58.5–92.3% ricinoleic acid in 72 USDA castor accessions. Rojas-Barros *et al.* [59] reported 9.9–88.6% ricinoleic and 1.7–83.2% oleic content in various seeds of an Indian accession PI 179729. Variation in fatty acid compositions of various castor cultivars has been reported earlier [58]. Difference was not observed between castor hybrids and varieties for ricinoleic acid content [58, 74]. Influence of environment on oil content and fatty acid composition was observed [75]. Low heterosis for oleic and ricinoleic acid of castor hybrids compared to the parents indicated the absence of dominant gene action [76].

Breeding for altered chemical composition of oil is limited by the natural variability existing in germplasm. Manipulation of biosynthetic pathways offers a number of opportunities to redesign plant metabolism towards production of specific fatty acid. Burgal *et al.* [77] have demonstrated that pathway engineering approaches can be used successfully to increase the yields of industrial feedstock in plants. Of late, research has been directed at understanding the metabolic pathways of ricinolein biosynthesis from oleic acid with a view to engineering its synthesis in alternative oilseed crops [78]. Draft genome sequence analysis has showed that most key castor oil metabolism genes are single-copy [70] genes. Chen *et al.* [79] have analysed expression profiles of 12 castor genes involved in fatty acid and TAG synthesis using quantitative reverse transcription-polymerase chain reaction technology. Ricinoleic acid accumulates in triacylglycerol (TAG) in endosperm. Synthesis of ricinoleate and TAG occur when seeds progress to stages of cellular endosperm development. Cagliari *et al.* [80] identified 26 genes representing six classes of enzymes that participate in different steps of TAG biosynthesis. They also characterized the expression profiles of these genes during seed development and, consequently during the accumulation of ricinoleic acid and TAG. The gene, *FAH12*, which is directly responsible for synthesis of ricinoleic acid, has been identified in endosperm of castor seed [81]. However, the transformed *Arabidopsis* expressing the castor *FAH12* did not demonstrate ricinoleic acid more than 17% concentration. These results suggested that the *FAH* gene by itself is not sufficient to produce high levels of ricinoleate in plants other than castor [82]. Recently, *PDAT1-2* has been identified as a gene that is an ER-located ricinoleate-specific phospholipid: diacylglycerol acyltransferase (PDAT) in seeds and is able to significantly increase the hydroxy fatty acid content in castor. Introduction of castor *PDAT1-2* into *Arabidopsis* CL37 produced an increase of 38% in TAG. The new candidate gene identified might further improve the level of ricinoleic acid in transgenic crops [83].

Castor is characterized by low levels of oleic acid and high levels of ricinoleic acid. Oleic acid is a monosaturated fatty acid generally believed to be good for health purpose. It helps lower harmful low-density lipoproteins (LDLs) in blood while retaining levels of beneficial high-density lipoproteins (HDLs) unchanged. Although high-oleic oils originally were designed for cooking oil, they have industrial uses. Modifying castor for high-oleic concentration can make it more useful for culinary purposes. Rojas-Barros *et al* [59] have identified a natural mutant line, OLE-1, with approximately 780 g/kg of oleic acid, compared with 40 g/kg of the standard castor oil. There was a six-fold decrease in ricinoleic acid content (140 g/kg) in the high-oleic mutant compared with more 870 g/kg in normal plants. The partial replacement of ricinoleic acid by oleic acid in OLE-1 has not affected significantly the biosynthesis of other fatty acids. High total tocopherol content (785 g/kg dry seed weight) has been also detected in OLE-1 at maturity as compared 605 g/kg dry seed weight in the standard genotype [84]. Oleic acid was shown to be the direct precursor of ricinoleic acid [85]. According to castor seed TAG biosynthesis, oleic acid is synthesized in the plastid and then exported to the cytoplasm following the standard fatty acid biosynthesis pathway [79]. Concentrations of oleic and ricinoleic acids are controlled by the genotype of individual seed embryo. Low oleic trait or high ricinoleic trait is dominant over high oleic or low ricinoleic; role of two independent genes (*ol*, *Ml*) with epistatic interaction was presumed in controlling oleic and ricinoleic concentrations in castor [86].

Castor Toxicity

The endosperm tissue of castor seeds contain two proteins, ricin (RCA_{60}) and *R. communis* agglutinin (RCA_{120}), which are highly toxic and lethal to eukaryotic cells [87]. Ricin is a potent cytotoxin with weak haemagglutinin properties. RCA_{120} is less toxic than ricin but a powerful haemagglutinin which functions as an allergen causes a health hazard during harvesting and processing [88]. After extraction of oil from seed, ricin remains in the meal. Castor is not foraged by animals as they sense toxicity in castor. Castor plants develop strategies to protect from their own toxins [89]. These toxins were first found in castor seeds in the late nineteenth century [90]. Ricin and RCA_{120} are synthesized and stored in protein bodies in endosperm cells of maturing castor seeds [87]. When seed germinates, the toxins are destroyed by hydrolysis within a few days. Ricin is found only in castor seed. Its biochemical activity is well characterized as a Type TI ribosome-inactivating enzyme. Ricin has an LD_{50} of approximately 2 μg/kg in standard mouse models and is thought to have a human LD_{50} of 3–30 μg/kg [91]. All parts of castor contain toxins but seeds contain the highest concentration of ricin [92, 93]. However, it is noteworthy that none of the toxic poison is carried into the oil. Because of the toxicity, countries such as the USA and EU countries do not grow castor extensively. There is also a fear of possibility of castor seed contaminating the adjacent crops particularly food crops.

Ricin is also a potential biological warfare agent. The US Centers for Disease Control (CDC) classifies ricin as a Class B biological terrorism threat. Because of this, US Homeland Security and the FBI carefully monitor interest in castor production. Ricin has been used by secret intelligence services as a weapon in many assassination attempts. Exposure to the toxin can occur by ingestion, injection or inhalation. Balint [94] reported over 700 cases of human intoxication dating back to the late 1800s. At present, no antidote or effective therapy is available for the treatment of ricin intoxication. Only symptomatic and supportive measures can be taken [92]. Inexpensive and simple methods of purification of ricin are raising biosafety concerns.

Castor meal contains about 5% ricin, which could pose a threat if not detoxified. Hence, safe handling and use of castor meal depends on neutralization of both the toxic and the allergenic components. The meal can be used as feed for livestock after detoxification [95]. Several methods are now available for detoxification of castor meal [96, 97]. Castor meal can be used as organic manure which prevents soil from exhausting. Castor meal contains high content of N (6.4%), phosphoric acid (2.55%) and potash (1%) and has moisture retention capacity. It also contains 20% crude protein, 50% sugar and 15% ash [98]. Castor meal is used to control nematodes in soils [99, 100]. Ricin can remain in the soil for about 2 years after castor harvesting [101]. However, the effect of residual toxin on the flora and fauna in soil is yet to be determined.

One logical approach for solving the biohazard problem associated with castor is to develop castor cultivars with reduced or zero levels of ricin in seeds. Varying concentrations of ricin was reported in castor genetic resources. Ricin content ranging from 2.9 to 10.8 mg/g of meal was estimated among 51 USDA castor accessions [73]. Pinkerton [102] reported remarkable diversity for ricin+RCA_{120} concentration ranging from 1.9 to 16 mg/g among 263 accessions received from USDA. Very low concentrations of ricin+RCA_{120} were estimated in two former USSR introductions, PI 257654 (1.5 mg/g) and PI 250623 (1.8 mg/g) and in an Iranian introduction, PI 222829 (1.9 mg/g). The USDA collections, PI 182987, PI 257657, PI 258368, PI 267802, PI 486318, which were introduced from India, Soviet Union, Brazil and Peru, respectively, contained 2.4–3.9 mg/g of these two toxins [103, 104]. Variability in ricin content ranging from 3.53 to 32 ng/μg of total proteins was reported among 20 germplasm collections from Brazil [105]. A team at Texas Tech University has been working for several years to reduce the concentration of ricin and other toxins found in castor seed using both conventional genetics and mutagenesis. The team has developed TTULRC, an open-pollinated germplasm population of castor having very low concentration of ricin + RCA_{120} (average=1.86 mg/g) [106]. A new castor variety, Brigham with seven to ten-fold reductions in ricin level has been developed. The average ricin content in Brigham ranges from 0.10 to 5.60 mg/g as compared to its high ricin parent, Hale, which contains around 12.2 mg/g ricin [104, 106]. Brigham variety has potential for future castor production in USA [107]. Individual plants as well as seeds of a single plant of Brigham have exhibited variation for ricin content. This variation for ricin levels and the variation due to seasonal and local environment have to be addressed further for validation of this variety [108].

The genes critical to production of ricin and the key allergen proteins in castor have been already isolated. The two sub-units (A & B) of ricin were found to be encoded by a single gene [109, 110]. The ricin genes exist in castor as a gene family. Twenty-eight putative genes for ricin family, 71 genes involved in biosynthesis of fatty acids and triacylglycerol, mainly ricinoleic were identified. An understanding of ricin synthesis will provide an opportunity to manipulate the genes for ricin reduction in castor through genetic engineering.

The biotechnological approach to block expression of ricin and 2S albumins in seed is being considered currently as an efficient technique to engineer non-toxic castor [111]. There are also considerations for genetic engineering of castor for producing valued oil known as epoxy instead of castor oil since the chemical structure of epoxy oil is very similar to that of castor oil. Novo Synthetix and Precision BioSciences, the biotechnology companies in Durham, North Carolina, have announced a biotech partnership-programme to develop a non-toxin castor by employing gene-editing technology to create non-ricin castor. A proprietary technology, Directed Nuclease Editor^{TM} (DNE), would be used for genetic modification of castor. As per the announcement, the DNE technology makes it possible to insert new genes into the sequence, or deactivate or remove unwanted genes or smaller genetic fragments of genes (http://www.precisionbiosciences.com). The researchers at the University of Southern Denmark are also working on ricin-free castor using genetic engineering approach.

Ricin is also known to have widespread application as a potential therapeutic agent for many human diseases. Experiments are being undertaken for production of genetically engineered ricin in heterologous systems which have implications in biodefense, treatment of AIDS, cancer immunotherapy besides use in disease-model systems such as those involving apoptosis [112]. Genetic engineering and expression of ricin was reported in tobacco [113].

Many countries are promoting a sustainable production of biofuel from castor despite of toxicity of castor plant. There is a great awareness that cultivation of castor can boosts rural economy, and government and private agencies are establishing transesterification plants with million tonnes capacity per day. USA and EU-countries which discontinued castor production earlier are now encouraging domestic production to reduce dependency on castor oil imports for domestic industry. In these countries, researchers are recommending stringent management and control measures, taking safeguard in transportation and storage of castor seed to eliminate contamination and restrictions on growing food crops on fields used for castor. European and US farmers have created national and international associations to promote castor-based biofuel. Development of castor cultivars with high oil content and low ricin levels is an important objective of current castor breeding programmes in these countries in order to make castor a hazard-free, economically important crop.

Need for Innovative Breeding for Frost-, Drought- and Salinity-Tolerant Castor

Climate change is expected to lead to longer dry spells, more intense droughts and floods, extreme temperatures and increase in soil salinity in several regions of the world. Frost or cold temperature, drought and salinity are the major abiotic stresses already limiting castor productivity. Therefore, research programmes should be initiated to develop cultivars with tolerance to these stresses which are going to be more intense in future. Castor plants at all stages of growth are very susceptible to frosts or cold temperatures. Shoots die at temperatures below $-1\,^{\circ}C$ and adult plants die at temperatures below -3 to $-4\,^{\circ}C$. Frost-free periods of 5–6 months are required to ensure good yields. Castor is grown as an annual crop in temperate regions. Making castor cold- or frost-tolerant is very necessary to improve productivity and popularization of castor cultivation in these regions. In order to cope with cold temperatures, breeding for cold-tolerant cultivars is the most straightforward approach that has been used in many crops.

The minimum temperature for germination of castor seed is 14–15 °C, maximum 35–36 °C and optimum 31 °C. Castor seed takes 7 days to germinate under optimum conditions, however, it varies from 10 days (at 19 °C) to 23 days (at 10 °C) depending up on soil temperature from time of planting to emergence [114]. Variability among castor genotypes for cold sensitiveness of seed germination has been reported in castor. Cold tolerance of seed germination sometimes may not necessarily associate with cold tolerance of seedling emergence and initial growth, as observed in some species [115]. Since cold temperatures intensity, duration and timing are unpredictable in field selection, a good selection method to evaluate cold tolerance under controlled temperature conditions is essential.

There is a phenomenal increase in occurrences of drought and duration of drought period across the globe effecting growth and productivity of crop species growing in arid and semi-arid regions. Therefore, drought-proofing technologies are the urgent necessity for stable and successful production of any crop species in these regions. Under severe drought conditions castor can yield some seed where other crops fail to yield, indicating its hardiness to withstand moisture stress. Because of its deep-root system, castor survives under moisture stress condition by extracting moisture from deep layers. Castor responses well to irrigation and the magnitude of response is higher with hybrids than varieties, in other words hybrids are more susceptible to moisture stress. Higher yields of castor can be realized with a moderate rainfall of 600–700 mm and fairly good yields can be obtained with a well distributed rainfall of 365–500 mm [116]. Though castor can withstand some drought, it needs at least 300 mm of precipitation during the vegetative period for growth. Castor plant response to water stress differs significantly depending on the intensity and duration of stress and stage of development. It is well established that moisture requirements of castor at different growth stages are not uniform. Drought stress during seed germination time reduces germination percentage and seedling growth severely. Moisture stress condition during reproductive stage decreases size and number of seed bearing racemes as well seed filling [117]. Increased duration of drought stress affects seed yield drastically [118, 119]. Increased moisture stress and temperature conditions reduce proportion of female flowers in racemes leading to reduction in yield.

In recent years, crop physiology and genomics have led to new insights in drought tolerance in crops providing breeders with new knowledge and tools for improving drought stress tolerance. Genetic improvement of castor for abiotic stress tolerance is relatively a new attempt. Drought resistance of castor seems to be related to an evident early growth response, an efficient stomatal control and the capacity to keep high net CO_2 fixation rates under water stress conditions [120]. Han and Kermode [121] observed production of drought-protective proteins called dehydrin-like proteins in castor seeds and seedlings in response to water-deficit-related stresses. Jin *et al.* [122] reported expression of four RcbZIP genes (2, 9, 22 and 36) in castor seedlings when exposed to drought stress suggesting the function of these genes in response to drought stress. Genotypic differences were observed in castor with respect to drought response [123, 124]. Seed yield reduction of less than 30% of what was realized under watered conditions was observed in germplasm accessions with low drought susceptibility index (<5%) [125]. Crop plants generally use more than one defence mechanism at a time to cope with drought; wax coating on leaf surface in castor is considered one of such mechanisms. Lakshmamma *et al.* [125] noticed significant increase in epicuticular wax load/bloom in the accessions with low drought susceptibility index when exposed to water stress conditions. Osmotic adjustment (OA) is another important mechanism facilitating drought stress tolerance in plants. A positive relationship (r=0.8539) was observed between OA of expanded castor leaf at 33 days after imposing stress and total seed yield under water-limited conditions. Genotypic variability for OA was observed; genotypes with high osmotic adjustment (HOA) capacity had higher total seed yield than genotypes with low osmotic adjustment (LOA). Castor hybrids were closer to their superior parents in terms of OA indicating heritable nature of OA. Accumulation of total soluble sugars (TSS) contributed largely to the OA in castor. Prolein accumulated higher in HOA genotypes than in LOA type by the end of the stress period. Similarly, higher accumulation of K^+ was observed in HOA as compared to LOA genotypes. The HOA genotypes also had higher excised leaf water retention capacity indicating that this trait appears to be useful screening criterion for drought tolerance in castor [126]. Schurr *et al.* [127] found that drought stress and re-watering after stress caused maturation of smaller leaves in a castor plant with a complete disorder in growth dynamics, carbohydrate and amino acid concentrations as well as sink-source related enzymes.

One of the strategies to overcome deficit moisture condition especially in castor growing arid and semi-arid regions is to evolve high-yielding drought-tolerant cultivars. The genetic resources have to be explored for natural genetic variability for response to drought stress. Breeding for drought-tolerant varieties has been accomplished in some crop species by selection for seed yield under real drought conditions in the field during non-rainy seasons. Long growing season of castor may be a constraint to adopt this approach as it requires full season field data but this approach would be suitable for preliminary screening of large populations.

Castor has an indeterminate growth habit and continues to produce seed in racemes until limited by lack of moisture or unfavourable conditions. Higher yields can be produced if castor is allowed to grow longer growing seasons. However, if grown under rainfed conditions, crop will undergo moisture stress during the major yield-contributing racemes, the primary and secondaries, formation stage. Castor planted early in June especially in India under rainfed conditions, produces higher quantity of seed in primary and secondary racemes as compared to delayed planting. Total yield was positively influenced by the moisture adequacy index and degree days i.e., temperature during the total reproductive period (initiation of primary to maturity of tertiary racemes) [128]. Early-maturing (120 days) or extra-early (<100 days) maturing castor varieties can escape drought and are desirable for drought prone regions. Several early and extra-early maturing high-yielding germplasm accessions have been reported in castor genetic resources; these can serve as base material for improving cultivars for short duration [19, 129].

Arid and semiarid regions are prone to have medium to high salt concentrations. Irrigation in semi-arid climates is a major cause of secondary salinization (that due to human activity). Castor displays some characteristics of salt tolerance such as Na+ exclusion from leaves after long-term exposure to high NaCl concentrations [130]. The salinity threshold for castor seed germination was found to be 7.1 dS/m (caused by NaCl). Reduction in leaf net photosynthetic rate and stomatal conductance was observed in castor when exposed to salt stress [131]. Distinct reduction in seed germination, growth parameters such as shoot growth and its dry weight, root growth and its dry weight and relative water content of plant was observed in castor with increase in the level of salinity from <2 to 8 dS/m [132, 133]. Differential response of castor varieties to salt stress was reported [134]. The relatively salt-tolerant cultivar 'Memphis' showed high relative emergence index and less fruit dry weight reduction under high salinity conditions [130]. Castor has higher tolerance to salinity than *Jatropha curcas*. This was attributed to higher electron partitioning from the photosynthetic electron transport chain to alternative sinks [135].

Precise abiotic stress levels at different growth stages can be obtained under controlled conditions.

However, space to test large populations is the main limiting factor under controlled conditions. To avoid this, the initial selection for stress-tolerant genotypes can be taken up in the target environment at different locations. Thus identified tolerant genotypes can be further confirmed under controlled conditions. Besides precision selection method, understanding of the genetic basis of stress tolerance is needed to plan breeding programmes. Simultaneously, traits contributing to stress tolerance in castor are to be identified and the correlations among different growth stages for tolerance need to be understood. Analyses of the responsive genes for stress tolerance in other crops have shown that numerous physiological, biochemical and molecular changes occur during stress periods and that several metabolic pathways are affected by different levels of stress, indicating that abiotic stress tolerance is more complex than perceived and a better understanding of the basic mechanisms is still needed [136].

The morphological, physiological and biochemical traits contributing to abiotic stress tolerance and their correlations with yield under stress and no stress conditions, and the molecular mechanisms of stress are yet to be understood fully. Once the stress conferring traits are established these can be transferred more accurately to different genetic backgrounds with assistance of molecular markers flanked to these traits without growing under target environments. Conventional breeding methods may be limited by the available genetic diversity within existing germplasm collections and lack of efficient selection criteria. It is important, therefore, to look for alternative strategies to develop stress-tolerant castor. A combined strategy considering breeding and genetic engineering tools hand-in-hand is needed to develop abiotic stress tolerant cultivars. Abiotic stress resistance breeding is a very complex programme despite availability of cutting-edge molecular technologies. Because such programmes require extremely efficient laboratories for the molecular analysis of large number of genotypes, and the selection of the best genotypes in a large test plots to utilize in breeding programmes.

Other Challenges and Priorities

Further challenges to be addressed are harvesting, resistance to diseases and insect pests and determination of region-based crop management systems. Harvesting of castor crop has always presented special problems owing to indeterminate growth habit. Castor plant develops racemes in a sequential order; therefore, maturity time and harvesting time of racemes are not uniform. Because the crop matures over a long period, three or more harvestings are necessary. The primary and secondary racemes are generally harvested first and the lateral racemes are in subsequent pickings at a fixed interval. The time of first picking varies with maturity duration of the cultivars. In India, the first picking is generally at 120 days after planting and the subsequent pickings will be at 1 month interval after the first picking.

Planting and harvesting is done by hand methods as well by mechanized harvesters. In the traditional practice, racemes are harvested manually at different days after planting. Manual harvesting is a labour-intensive operation. Mechanical harvesting requires synchronized maturity of all racemes on a plant. Introduction of dwarf plant type varieties, the development of strippers and combine harvester-huller allowed full mechanization of the crop. Castor plant type with no branches, short height with a single long and wide productive raceme or a short castor plant type with a few branches and racemes having synchronized maturity can be more suitable for mechanized harvesting. In traditional castor-growing regions suitable machines are not available for harvesting of castor crop. Hand harvesting is still in practice in many countries. In India castor is hand-harvested, in South Africa and Australia modified wheat headers are used for harvesting and in the USA expensive harvesters are used which shake capsules from plants by jarring plants at their bases. The high cost of the combine harvester is limiting castor growers to adopt mechanized harvesting.

Castor is attacked by many disease and insect pests. Resistance sources are available in genetic resources for many of the diseases [15]. Effective and eco-friendly means to control the major diseases of castor, such as *Fusarium* wilt and *Botrytis* grey mould and major insect pests have to be developed to sustain increased productivity in castor. Even though there were no studies on impact of global warming induced climate change on castor but it is expected to trigger major changes in population dynamics of insect pests as well as insect and disease biotypes, activity and abundance of natural enemies and efficacy of existing crop protection technologies. Development of eco-friendly products of biological origin can be developed for reducing high chemical plant protection costs. Considering the impact of global warming, temperature-tolerant strains have to be identified to use in bio-pesticides.

Low-input cost crop production technologies with higher input efficiencies based on climatic changes need to be developed to sustain castor production. Research on region or location-specific production and protection technologies should be given priority. Location-wise soil fertility status needs to be assessed for reducing input cost and increasing the efficiency of input use. Balanced fertilization with consideration for soil fertility status should be addressed on priority basis. Cropping system based fertilizer management has to be determined for reducing input cost and realizing higher yields. Conservation agriculture practices have to be developed for different agro-eco regions.

For much higher production, the governments and the industry stakeholders should provide financial, infrastructure, scientific and technical support to the farming community. The success in castor production in India is mainly because of development of high-yielding castor hybrids. The hybrids were quickly adopted and spread fast among farmers because of high income generation. Well-developed infrastructure and incentive structures have helped castor production become successful and also enhanced the quick commercialization of castor seed in India. The grey areas of public–private-partnership can be exploited to the advantage of individual country's economy. The international collaborations will increase both the efficiency and speed of research in developing castor as a bioenergy crop. This would further enable castor farmers to realize the higher value of their produce.

Establishing well-organized seed multiplication systems, seed supply chain and commercial market is very important for faster adoption of castor and its persistence in any country. Quality of the seed should be given utmost importance. Heavy investments of governments and industry on public research funding and human resource development especially in the fields of crop breeding, agronomy, crop protection and extension is also an important factor for castor success in any country. More focused efforts are required both for the scientific and product research aspects as well as for market research. Timely and adequate supply of critical inputs at subsidized costs will help to extend area under castor cultivation especially in marginal rainfed lands. Credit facility to small land holders would encourage castor cultivation. Fixing minimum support price for castor by governments prior to commencement of season would ensure income to castor farmers. The market prices should be regulated to avoid middle man to make castor more profitable.

Many countries especially in Africa are encouraging castor cultivation in marginal or degraded lands recognized as food insecure areas in arid and semi-arid regions. But in promoting castor in these lands one should keep in mind that these lands would invariably produce low yields and low economic returns, if the problems associated with them are not addressed. The yields and returns in marginal environments should not be compared with those come from productive lands. Research in castor should address the effect of best management practices on crop yields in marginal environments. An integral assessment of the crop productivity and the impact of resource use, and socio-economic factors should be carried out before launching large-scale castor production systems in marginal environments.

To sustain castor cultivation in new areas, it is essential to assess the production potential of castor crop, farm production capacity of small farmers, adaption and dissemination of castor production technologies, ecological sustainability of castor production, food security in adopting castor, possibilities for commercialization and socio-economic impact in new niches. These are crucial for sustaining castor cultivation. Farmers should be trained and guided in castor cultivation aspects. Extension services can encourage castor adoption in new areas through dissemination of information on castor cultivation which would help generating interest in stakeholders. The physical logistics such as warehousing, scientific management of stocks, and transportation are also to be improved.

Conclusion

Concerted research efforts have transformed castor from a mere invasive, colonizing plant species into a most-sought- after high-value crop. There is a tremendous scope to establish castor as an added crop production option to smallholder farmers and to provide significant returns on investment as well as help build a sustainable agriculture in future in many quarters. Given the industrial nature of the castor oil and high global demand, its value would increase year after year with the access to deep-processing products. The governments and private stakeholders should come forward to support castor cultivation and to establish industries related to castor processing and production of castor derivatives to realize the great economic potential of castor. Interdisciplinary collaborations in research projects are needed to ensure sustainability of castor adoption in newer areas. The current limitations for extensive cultivation of castor can be overcome by introducing ricin-free cultivars along with modified oil profile characteristics. Castor-based biodiesel is expected to be a substantially cheaper alternative than that developed from crops such as canola and soybeans. Castor-based biodiesel presents a favourable impact on the environment because of biodegradability and lower emission characteristics. The ever-expanding end uses of castor oil and its derivatives would make castor crop imperative for commerce.

References

1. Sue Eland. *Ricinus communis*. Plant Biographies 2008:1–4. Available from: URL: http://www.plantlives.com.
2. Kulkarni LG, Ramamurthy GV. Castor. ICAR, New Delhi; 1959.
3. Moshkin VA, editor. Castor. Amerind Publishing Co. Pvt Ltd, New Delhi; 1986.
4. Carter S, Smith AR. Euphorbiaceae Flora of Tropical East Africa. AA Balkema Publishers, Rotterdam, Netherlands; 1987.
5. Weibel RO. The castor: oil plant in the United States. Economic Botany 1948;2:273–83.
6. Severino LS, Auld DL, Baldanzi M, Candido MJD, Chen G, Crosby W, *et al.* A review on the challenges for increased production of castor. Agronomy Journal 2012;104:853–80.
7. Wu Z. Chinese castor oil market. In Proceedings of Global Castor Conference 2011; 2011 February 19; Ahmedabad, India.

8. Abdulkareem AS, Jimoh A, Afolabi AS, Odigure JO, Patience D. Production and characterization of biofuel from non-edible oils: an alternative energy sources to petrol diesel. In: Ahmed AZ, editor. Energy conservation. InTech. Open access publisher; 2012. p. 171–96. DOI: 10.5772/2788.

9. Auld DL, Zanotto MD, McKeon T, Morris JB. Oil crops. In: Vollmann J, Rajcan I, editors, Handbook of Plant Breeding Volume 4. Springer Science + Business media, New York; 2009. p. 317–32.

10. Prasad RBN. Technology infusion for sustained growth in domestic consumption. In Proceedings of Global Castor Conference 2011; 2011 February 19; Ahmedabad, India.

11. Shrirame HY, Panwar NL, Bamniya BR. Bio diesel from castor oil – a green energy Option. Low Carbon Economy 2011;2:1–6.

12. Ogunniyi DS. Castor oil: a vital industrial raw material. Bioresource Technology 2006;97:1086–91.

13. Panwar NL, Shrirame HY, Bamniya BR. CO_2 Mitigation potential from biodiesel of castor seed oil in Indian context. Clean Technologies and Environmental Policy 2010; 12:579–82. doi: 10.1007/s10098-009-0269-5

14. Gui MM, Lee KT, Bhatia S. Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock. Energy 2008;33:1646–53.

15. Anjani K. Castor genetic resources: a primary gene pool for exploitation. Industrial Crops and Products 2012;35:1–14.

16. Fanan S, Medina PF, Camargo MBP. Description of agronomic characteristics and harvest time evaluation in the yield of castor bean cultivar IAC 2028. Bragantia 2009;68:415–22.

17. Kittock DL, Williams JH. Castor bean production as related to length of growing season. I. Date of planting tests. Agronomy Journal 1967;59:456–8.

18. Anjani K, Hegde DM. Biodiversity in indigenous castor. In: Kannaiyan S, Venkatarmana K, editors; National Consultation Workshop on Agrobiodiversity Hot Spots and Access and Benefit Sharing. Annamalai University, Annamalinagar, TN, India. 2007; p. 41–2.

19. Anjani K. Extra-early maturing germplasm for utilization in castor improvement. Industrial Crops and Products 2010;31:139–44.

20. James TA, Harden GJ. Flora of New South Wales. National herbarium. N S W. Royal Botanic Garden, Sydney, Australia; 1990.

21. Mehmood F, Khan AUH, Khan Z. Appraisal of ecological significance of *Ricinus communis* Linn. in the wasteland of Lahore, Pakistan. Biologia (Pakistan) 2011;57:97–103.

22. Rahat I. Observations on the growth strategies of 5 colonizers species of wasteland [dissertation]. Pakistan: Govt. College Lahore; 1996.

23. Huang H, Yu N, Wang L, Gupta DK, He Z, Wang K, *et al.* The phytoremediation potential of bioenergy crop *Ricinus communis* for DDTs and cadmium co-contaminated soil. Bioresource Technology 2011;102:11034–8.

24. Bauddh K, Singh RP. Cadmium tolerance and its phytoremediation by two oil yielding plants *Ricinus communis* (L.) and *Brassica juncea* (L.) from the contaminated soil. International Journal of Phytoremediation 2012;14:772–85.

25. Olivares AR, Carrillo-Gonzalez R, González-Chavez MDCA, Soto Hernandez RM. Potential of castor bean (*Ricinus communis* L.) for phytoremediation of mine tailings and oil production. Journal of Environmental Management 2013;114:316–23.

26. Vwioko DE, Anoliefo GO, Fashem SD. Metal concentration in plant tissues of *Ricinus communis* L. (castor oil) grown in soil contaminated with spent lubricating oil. Journal of Applied Sciences and Environmental Management 2006;10:12–134.

27. Andreazza R, Bortolon L, Pieniz S, Camargo FAO. Use of high-yielding bioenergy plant castor bean (*Ricinus communis* L.) as a potential phytoremediator for copper-contaminated soils. Pedosphere 2013;23:651–61.

28. Mahmud R, Inoue N, Kasajima S, Kat M, Shaheen R, Miah MAM, *et al.* Response of common buckwheat and castor oil plant against different levels of soil arsenic concentration: a comparative study. Fagopyrum 2006;23: 45–51.

29. Melo EEC, Costa ETS, Guilherme LRG, Faquin V, Nascimento CWA. Accumulation of arsenic and nutrients by castor bean plants grown on an As-enriched nutrient solution. Journal of Hazardous Materials 2009;168:479–83.

30. Pandey VC. Suitability of *Ricinus communis* L. cultivation for phytoremediation of fly ash disposal sites. Ecological Engineering 2013;57:336–41.

31. Mamta T, Padma V, Naik SN, Davies P. Oil bearing seasonal crops in India: energy and phytoremediation potential. International Journal of Energy Sector Management 2007;7:338–54.

32. Oladoja NA, Aboluwoye, CO, Oladimeji YB, Ashogbon AO, Otemuyiwa IO. Studies on castor shell as a sorbent in basic dye contaminated wastewater remediation. Desalination 2008;227:190–203.

33. Vanaja M, Jyothi M, Ratnakumar P, Vagheera P, Reddy PR, Lakshmi NJ, *et al.* Growth and yield responses of castor bean (*Ricinus communis* L.) to two enhanced CO_2 levels. Plant Soil and Environment 2008;54:38–46.

34. Brigham RD. Registration of castor variety Dawn. Crop Science 1970;10:457.

35. Brigham RD. Registration of castor variety Hale. Crop Science 1970;10:457.

36. Brigham RD. Registration of castor variety Lynn. Crop Science 1970;10:457.

37. Brigham RD. Castor: Return of an Old Crop. New Crops, John Wiley & Sons, New York; 1993. p. 380–3.

38. Labalette F, Estragnat A, Messean A. Development of castor bean production in France. In: Janick J, editor. Progress in New Crops. ASHS Press, Alexandria, VA; 1996 p. 340–2.

39. Vieira RM, Lima EF, Batista FAS. Diagnostic and prospects castor in Brazil. In: Thematic Meeting Raw Oilseeds Brazil: Diagnosis, Perspectives and Research Priorities. Embrapa-CNPA. Documents, 63, Campina Grande; 1997. p. 139–50. (in Portuguese).

40. White ES. Breeding new castor beans. Journal of Heredity 1918;9:195–200.

41. Stein H. An analysis of a case of hybrid vigour in castor bean. Plant Bulletin Research Council, Israel 1958;8 : 5 (Plant Breeding Abstracts 29 : 2382).

42. Gopani DD, Kabaria MM, Patel RH. Study of hybrid vigour in castor. Indian Journal of Agricultural Sciences 1968;38:520–7.

43. Joshi WV. Some variations in the inflorescence of the castor plant. Poona Agric. College Magazine 1926;18:26–9.

44. Shifriss O. Sex instability in Ricinus. Genetics 1956;41: 265–80.

45. Shifriss O. Sex categories in Ricinus. Weiz Institute Report (1955–1956); 1957: 154–5.

46. Kulkarni LG, Ankineedu G. A new sex phenotype in castor. Indian Journal of Agricultural Sciences 1966;36:255–7.

47. Gopani DD, Kabaria MM, Patel RH. Study of sex reversion in castor. Indian Journal of Agricultural Sciences 1969;39:255–8.

48. Claassen CE, Hoffman A. The inheritance of the pistillate character in castor and its possible utilization in the production of commercial hybrid seed. Agronomy Journal 1950;42:79–82.

49. Zimmerman LH, Smith JD. Production of F_1 seed in castor beans by use of sex genes sensitive to environment. Crop Science 1966;6:406–9.

50. Ankineedu G, Rao NGP. Development of pistillate castor. Indian Journal of Genetics and Plant Breeding 1973;33: 416–22.

51. Tewari DD. Castor revolution in Gujarat, India: What made it successful? IIMA Working Paper No. 1254; 1995.

52. Gangwar B, Sharma SK, Yadav RL, editors. Oilseed Based Cropping Systems: Issues and Technologies. Project Directorate for Cropping Systems Research, India; 2002.

53. Sailaja M, Tarakeswari M, Sujatha M. Stable genetic transformation of castor (*Ricinus communis* L.) via particle gun-mediated gene transfer using embryo axes from mature seeds. Plant Cell Reports 2008;27:1509–19. doi: 10.1007/s00299-008-0580-3.

54. Sujatha M, Reddy TP, Mahasi MJ. Role of biotechnological interventions in the improvement of castor (*Ricinus communis* L.) and *Jatropha curcas* L. Biotechnology Advances 2008;26:424–v35. doi: 10.1016/ j.biotechadv.2008.05.004

55. Xu W, Fei L, Lizhen L, Aizhong L. Genome-wide survey and expression profiles of the AP2/ERF family in castor bean (*Ricinus communis* L.). BMC Genomics 2013;14:785. doi: 10.1186/1471-2164-14-785

56. Zhang S-D, Ling L-Z. Genome-wide identification and evolutionary analysis of the SBP-Box gene family in castor bean. PLoS ONE 2014;9:e86688. doi: 10.1371/ journal.pone.0086688.

57. Gedil M, Kolade F, Raji A, Ingelbrecht I, Dixon A. Development of molecular genomic tools for verification of intergeneric hybrids between castor bean (*Ricinus communis* L.) and cassava (*Manihot esculenta* Crantz). Journal of Food, Agriculture and Environment 2009;7:534–9.

58. Da Silva Ramos LC, Tango JS, Savi A, Leal NR. Variability for oil and fatty acid composition in castor bean varieties. Journal of the American Oil Chemists' Society 1984;61: 1841–3.

59. Rojas-Barros P, de Haro A, Munoz J, Fernandez-Martinez JM. Isolation of a natural mutant in castor with high oleic/low ricinoleic acid content in oil. Crop Science 2004;44:76–80.

60. Okoh JO, Ojo AA, Vange T. Combining ability and heterosis of oil content in six accessions of castor at Makurdi. Nature and Science 2003;5:18–23.

61. Zimmerman LH. Castor beans: a new crop for mechanized production. Advances in Agronomy 1958;X:257–88.

62. Moshkin VA, Dvoryadkina AG. Cytology and genetics of quality characteristics. In: Moshkin VA editor, Castor. Amerind, New Delhi; 1986. p. 93–103.

63. Fernandaz-Martinez JM, Velasco L. Castor. In: Gupta SK, editor. Technological Innovations in Major World Oil Crops. Volume 1: Breeding. Springer Science + Business media, New York; 2012. p. 237–66.

64. Pathak HC, Dagaria CJ, Parmar SK. Heterosis and genetic architecture of oil content in castor (*Ricinus communis* L.). Madras Agricultural Journal 1986;73:328–33.

65. Dobariya KL, Patel ID, Patel PS, Patel VJ. Combining ability and genetic architecture of oil content in castor (*Ricinus communis* L.). Journal of Oilseeds Research 1989;6:92–6.

66. Lakshminarayana G, Paulose MM, Neeta Kumari B. Characteristics and composition of newer varieties of Indian castor seed and oil. Journal of the American Oil Chemists' Society 1984;61:1871–2.

67. Ramanjaneyulu AV, Madhavi A, Reddy AV, Neelima TL. Influence of date of sowing and irrigation scheduling on *rabi* castor (*Ricinus communis*) in Peninsular India. Indian Journal of Agronomy 2013;58:100–4.

68. Alirezalu A, Farhadi N, Shirzad H, Saeid H. The effect of climatic factors on the production and quality of castor oil. Nature and Science 2011;9:15–9.

69. Severino LS, de Albuquerque WG, de Oliveira MA, Gomes JA, Milani M. Variability on percentage of seed hulls of castor seed and its importance to breeding. Revista Ciencia Agronomica 2009;40:94–8.

70. Chan AP, Crabtree J, Zhao Q, LorenziH, Orvis J, Puiu D, *et al.* Draft genome sequence of the ricin-producing oilseed castor bean. Nature Biotechnology 2011;28:951–6.

71. Kim HU, Jung SJ, Lee KR, Kim EH, Lee SM, Roh KH, Kim JB. Ectopic overexpression of castor bean LEAFY COTYLEDON2 (LEC2) in Arabidopsis triggers the expression of genes that encode regulators of seed maturation and oil body proteins in vegetative tissues. FEBS Open Bio 2014;4:25–32.

72. Da Silva NL, Batistella CB, Maciel MRW, Filho RM. Biodiesel production from castor oil: optimization of alkaline ethanolysis. Energy Fuels 2010;23:5636–42.

73. Bhardwaj HL, Mohamed AI, Webber III CL, Lovell GR. Evaluation of castor germplasm for agronomic and oil characteristics. In: Janick J, editor. Progress in New Crops. ASHS Press, Alexandria, VA. 1996; p. 342–6.

74. Ravikishan P, Mev Singh, Prasad MVR. Composition and variability of oil quality in castor and linseed. In: Nagaraj G, Muralidharudu Y, Ravi Kishan P, Mev Singh, editors. Oilseed Quality and Value Added Products. Directorate of Oilseeds Research, Hyderabad, India; 1995. p. 19–24.

75. Cheema NM. Yield and chemical composition of castor bean (*Ricinus communis L.*) as influenced by environment [dissertation]. Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, Pakistan; 2011.

76. Lavanya C, Murthy IYLN, Nagaraj G, Mukta N. Prospects of castor (*Ricinus communis* L.) genotypes for biodiesel production in India. Biomass and Bioenergy 2012;39:204–9.

77. Burgal J, Shockey J, Lu C, Dyer J, Larson T, Graham I, *et al.* Metabolic engineering of hydroxy fatty acid production in plants: RcDGAT2 drives dramatic increases in ricinoleate levels in seed oil. Plant Biotechnology Journal 2008;6: 819–31.

78. Brown PA, Johan TMK, David S, Melanie F, Larson TR, Graham IA, *et al.* Tissue-Specific whole transcriptome sequencing in castor, directed at understanding triacylglycerol lipid biosynthetic pathways. PLoS ONE 2012;7(2). doi: 10.1371/journal.pone.0030100

79. Chen QG, Charlotta T, Xiaohua H, Tasha N, Thomas A. McKeon, Debbie Laudencia-Chingcuanco.2007. Expression profiles of genes involved in fatty acid and triacylglycerol synthesis in castor bean (*Ricinus communis* L.). Lipids 2007;42:263–74.

80. Cagliari A, Margis-Pinheiro M, Loss G, Mastroberti AA, de Araujo Mariath JE, Margis R. Identification and expression analysis of castor bean (*Ricinus communis*) genes encoding enzymes from the triacylglycerol biosynthesis pathway. Plant Science 2010;179:499–509.

81. van de Loo FJ, Broun P, Turner S, Somerville C. An oleate 12-hydroxylase from *Ricinus communis* L. is a fatty acyl desaturase homolog. Proceedings of National Academy of Science USA 1995;92:6743–7.

82. McKeon TA, Lin JT. Biosynthesis of ricinoleic acid for castor oil production. In: Kuo TM, Gardner HW, editors. Lipid Biotechnology. Marcel Dekker, New York; 2002; p. 129–39.

83. Kim UH, Kyeong-Ryeol L, Young Sam G, Jin Hee J, Mi-Chung S, Jong Bum K. Endoplasmic reticulum-located PDAT1-2 from castor bean enhances hydroxy fatty acid accumulation in transgenic plants. Plant Cell Physiology 2011;52:983–93.

84. Velasco L, Rojas-Barros PR, Fernandez-Martınez JM. Fatty acid and tocopherol accumulation in the seeds of a high oleic acid castor mutant. Industrial Crops and Products 2005;22:201–6.

85. James AT, Hadaway HC, Joan P, Webb W. The biosynthesis of ricinoleic acid. Biochemical Journal 1965;95:448–52.

86. Rojas-Barros PR, Haro A, Fernandez-Martınez JM. Inheritance of high oleic/low ricinoleic acid content in the seed oil of castor mutant OLE-1. Crop Science 2005;45:157–62. doi: 10.2135/cropsci2005.0157

87. Lord MJ, Roberts LM, Robertus JD. Ricin: structure, mode of action, and some current applications. Journal of Federation of American Societies for Experimental Biology 1994;8:201–8.

88. Chen GQ, He X, McKeon TA. A simple and sensitive assay for distinguishing the expression of ricin and *Ricinus communis* agglutinin genes in developing castor seed (*R. communis* L). Journal of Agricultural Food Chemistry 2005;53:2358–61.

89. Frigerio L, Roberts LM. The enemy within: ricin and plant cells. Journal of Experimental Botany 1998;49:1473–80.

90. Franz H. Advances in Lectin Research. SpringerVeriag, Beriin; 1988.

91. Ovenden PBS, Benjamin R, Gordon, Christina KB, Bob M., Simone R., David JB. Cultivar Determination of *Ricinus communis* via the Metabolome: a Proof of Concept Investigation. Published by Human Protection and Performance Division, DSTO Defence Science and Technology Organization, Australia; 2009.

92. Abrin R. Two dangerous poisonous proteins, Jiri Patocka, The ASA Newsletter 2001: 20–5.

93. Steenkamp PA. Chemical analysis of medicinal and poisonous plants of forensic importance in South Africa [dissertation]. University of Johannesburg, Johannesburg, South Africa; 2005.

94. Balint GA. Ricin: the toxic protein of castor oil seeds. Toxicology 1974;2:77–102.

95. Audi J, Belson M, Patel M, Schier J, Osterloh J. Ricin poisoning. A comprehensive review. Journal of the American Medical Association 2005;294:2342–51.

96. Anandan S, Kumar G, Ghosh J, Ramachandran K. Effect of different physical and chemical treatments on detoxification of ricin in castor cake. Animal Feed Science and Technology 2004;120:159–68.

97. Horton J, Williams MA. A cooker-extruder for deallergenation of castor bean meal. Journal of American Society of Chemists' Society 1989;66:227–31. doi: 10.1007/BF02546065.

98. Barnes DJ, Baldwin BS, Braasch DA. Degradation of ricin in castor seed meal by temperature and chemical treatment. Industrial Crops and Products 2009;29:509–15. doi: 10.1016/j.indcrop.2008.09.006.

99. Rao MS, Parvatha Reddy P, Sukhada M, Nagesh M. Pankaj Management of root-knot nematode on egg plant by integrating endomycorrhiza (*Glomus fasciculatum*) and castor (*Ricinus communis*) cake. Nematologia Mediterranea 1998;26:217–9.

100. Tiyagi Sartaj A, Shamim A. Biological control of plant parasitic nematodes associated with chick pea using oil cakes and *Paecilomyces lilacinus*. Indian Journal of Nematology 2004;34:44–8.

101. Eliboroda BA. Quantifying ricin in agricultural soils [dissertation]. Tech University, Texas; 2002.

102. Pinkerton 1997. Selection of castor with divergent concentrations of ricin and RCA using radial immune diffusion [dissertation]. Texas Tech University, Lubbock, USA; 1997.

103. Pinkerton SD, Rolfe R, Auld DL, Ghetie V, Lauterbach BF. Selection of castor for divergent concentrations of ricin and *Ricinus communis* Agglutinin. Crop Science 1999;39:353–7.

104. Auld DL, Rolfe RD, McKeon TA. Development of castor with reduced toxicity. Journal of New Seeds 2001;3:61–9.

105. Baldoni AB, de Carvalho MH, Sousa NL. Variability of ricin content in mature seeds of castor bean. Pesquisa Agropecuaria Brasileira, Brasilia, 2011;46:776–9.

106. Auld DL, Pinkerton SD, Boroda E, Lombard KA, Murphy CK, Kenworthy KE, *et al.* Registration of TTU-LRC castor germplasm with reduced levels of ricin and RCA120. Crop Science 2003;43:746.

107. Trostle CL, Wallace SM, Auld D. Keys and Concerns for Castor Production in Texas: The 'First Things' you Need to Know. Texas A&M Agri Life Research & Extension Center, Lubbock, TX; 2012.

108. Wettasinghe RMS. Development of castor (*Ricinus communis*) var. Brigham with ultra low ricin content by

analyzing soluble seed proteins [dissertation]. Texas Tech University, Lubbock, USA; 2012.

109. Halling K, Halling A, Murray E, Ladin B, Houston L, Weaver R. Genomic cloning and characterization of a ricin gene from *Ricinus communis*. Nucleic Acids Research 1985;13:8019–33.

110. Tregear JW, Roberts LM. The lectin gene family of *Ricinus communis*: Cloning of a functional ricin gene and three lectin psedogenes. Plant molecular Biology 1992;18:515–25.

111. Chen QG, Ahn Y-J, Yang L. Engineering new crops for safe castor oil production. In: Xu Z, Li J, Xue Y, Yang W, editors. Biotechnology and Sustainable Agriculture 2006 and Beyond; 2007. p. 227–30.

112. Sehnke CP, Ferl RJ. Processing of preproricin in transgenic tobacco. Protein Expression and Purification 1999;15: 188–95.

113. Sehnke PC, Pedrosa L, Paul AL, Frankel AE, Ferl RJ. Expression of active processed ricin in transgenic tobacco. Journal of Biological Chemistry 1994;269:22473–6.

114. Weiss EA. Oilseed Crops, 2nd ed. Blackwell Science, Oxford; 2000.

115. Cheema NM, Malik MA, Qadir G, Rafique MZ, Nawaz N. Influence of temperature and osmotic stress on germination induction of different castor bean cultivars. Pakistan Journal of Botany 2010;42:4035–41.

116. Hegde DM, Babu SN. Castor. In: Rajendra P, technical editor. Textbook of Field Crops Production. Indian Council of Agricultural Research, New Delhi 2002; p. 579–603.

117. Koutroubas SD, Papakosta DK, Doitsinis A. Water requirements for castor oil crop (*Ricinus communis* L.) in a Mediterranean climate. Journal of Agronomy and Crop Science 2000;184:33–41.

118. Moghaddam PR, Bromand Rezazadeh Z, Mohamad Abadi AA, Sharif A. Effects of sowing dates and different fertilizers on yield, yield components, and oil percentage of castor bean *(Ricinus communis* L.). Journal of Agronomy 2009;6:303–13.

119. Laei Gh. The effect of drought stress on grain yield and oil rate and protein percentage of four varieties castor in climatic conditions of damghan. Journal of Chemical Health Risks 2012;2:37–42.

120. Sausen, LT, Rosa MLG. Growth and carbon assimilation limitations in *Ricinus communis* (Euphorbiaceae) under soil water stress conditions. Acta Botanica Brasilica 2010;24:648–54.

121. Han B, Kermode AR. Dehydrin-like proteins in castor bean seeds and seedlings are differentially produced in response to ABA and water-deficit-related stresses. Journal of Experimental Botany 1996;47:933–9.

122. Jin Z, Xu W, LiuA. Genomic surveys and expression analysis of bZIP gene family in castor bean (*Ricinus communis* L.). Planta 2014;239:299–312.

123. Zade EM, Myandoab PM. Studying genetic diversity and selecting castor bean's most possible genotype based on drought tolerance indices. Annals of Biological Research 2012;3:3089–92.

124. Radhamani T, Ushakumari R, Amudha R, Anjani K. Response to water stress in castor (*Ricinus communis* L.) genotypes under *in vitro* conditions. Journal of Cereals and Oilseeds 2012;3:56–8.

125. Lakshmamma P, Lakshmi P, Lavanya C, Anjani K. Growth and yield of different castor genotypes varying in drought tolerance. Annals of Arid Zone 2009;48:35–9.

126. Babita M, Maheswari M, Rao LM, Shanker AK, Rao DG. Osmotic adjustment, drought tolerance and yield in castor (*Ricinus communis* L.) hybrids. Environmental and. Experimental Botany 2010;69:243–9. doi: 10.1016/ j.envexpbot.2010.05.006

127. Schurr U, Hechenberger U, Herdel K, Walter A, Feil R. Leaf development in *Ricinus communis* during drought stress: dynamics of growth processes, of cellular structure and sink-source transition. Journal of Experimental Botany 2000;51:1515–29.

128. Vijaya Kumar P, Ramakrishna YS, Ramana Rao BV, Victor US, Srivastava NN, Subba Rao AVM. Influence of moisture, thermal and photoperiodic regimes on the productivity of castor beans (*Ricinus communis* L.). Agricultural and Forest Meteorology 1997;88:279–89.

129. Anjani K, Jain SK. Castor. In: Dhillon BS, Tayagi RK, Saxena S, Agrawal A, editors. Plant Genetic Resources: Oilseed and Cash Crops. Narosa Publishing House, New Delhi, India; 2004. p. 105–17.

130. Sun Y, Niu G, Osuna P, Ganjegunte G, Auld D, Zhao L, *et al.* Seedling emergence, growth, and leaf mineral nutrition of *Ricinus communis* L. cultivars irrigated with saline solution. Industrial Crops and Products 2013;49:75–80.

131. Zhou GS, Ma BL, Li J, Feng CN, Lu JF, Qin P. Determining salinity threshold level for castor bean emergence and stand establishment. Crop Science 2010;50:2030–6.

132. Severino LS, Cordoba GOJ, Zanotto MD, Auld DL. The influence of the caruncle on the germination of castor seed under high salinity or low soil water content. Seed Science and Technology 2012;40:140–4.

133. Silva SMS, Alves AN, Ghey HR, Beltrao NEM, Severino LS, Soares FAL. Growth and production of two cultivars of castor bean under saline stress. Revista Brasileira de Engenharia Agricola e Ambiental 2008;12:335–42.

134. Raghavaiah CV, Lavanya C, Kumaran S, Jeevan Royal TJ. Screening castor (*Ricinus communis*) genotypes for salinity tolerance in terms of germination, growth and plant ion composition. Indian Journal of Agricultural Sciences 2006;76:196–9.

135. Lima Neto MC, Lobo AK, Martins MO, Fontenele AV, Silveira JA. Dissipation of excess photosynthetic energy contributes to salinity tolerance: a comparative study of salt-tolerant *Ricinus communis* and salt-sensitive *Jatropha curcas*. Journal of Plant Physiology 2014;171:23–30.

136. da Cruz RP, Sperotto RA, Cargnelutti D, Adamski JM, Tatiana de FreitasTerra, Fett JP. Avoiding damage and achieving cold tolerance in rice plants. Food and Energy Security 2013;2:96–119.