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Castor Breeding: Principles, Practices, Objectives, Traits, Challenges, and Advancements

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Abstract

The castor bean is a vital industrial oilseed crop valued for its high ricinoleic acid content and diverse commercial applications. This paper reviews the principles, practices, objectives, and challenges of castor breeding, emphasizing hybridization, mutation, and selection methods alongside modern tools such as marker-assisted selection, genetic transformation, and omics technologies. Key breeding objectives include enhancing oil yield and quality, developing resistance to biotic and abiotic stresses, improving plant architecture for mechanized harvesting, and reducing toxic compounds like ricin and allergens. Despite limitations posed by narrow genetic diversity, complex sex expression, and biosafety concerns, recent advancements—such as genome sequencing, molecular marker development, and transgenic approaches—have accelerated progress in castor improvement. The study highlights future directions in broadening the genetic base, strengthening climate resilience, and integrating sustainable practices to ensure the crop's global relevance and economic value.

Keywords: *Castor breeding, Genetic improvement, Hybridization, Marker-assisted selection.*

1. Introduction

The castor bean (Ricinus communis L.) is a vital oilseed crop with significant global economic importance [1]. Belonging to the family Euphorbiaceae, it is considered a monospecific genus with a diploid chromosome number of 2n=20 [3]. Originating in Eastern Africa, possibly Ethiopia, the wild ancestor of cultivated castor was a woody perennial plant characterized by dehiscent capsules and small seeds [5]. Over approximately 3200 years of domestication, the species underwent substantial morphological changes, resulting in the semi-woody annual plant predominantly grown today [5].

India stands as the leading global producer of castor, contributing over 60% to the world's total output [1]. This significant production underscores the crop's crucial role in the agricultural economy of the region, generating substantial foreign exchange through the export of both castor beans and oil [1].

Castor oil is highly valued for its unique chemical composition, primarily due to the high content of ricinoleic acid, which typically constitutes 84% to 90% of its total fatty acid profile [7]. This hydroxylated fatty acid imparts distinctive properties to the oil, including high viscosity, oxidative stability, and an extended shelf life [8]. Consequently, castor oil

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finds diverse applications across numerous industries, including pharmaceuticals, cosmetics, biofuel production, acting as a lubricant, and in the manufacturing of polymers, soaps, and coatings [1].

Given its economic significance and the diverse applications of its oil, continuous improvement of castor through breeding programs is of paramount importance. These efforts aim to enhance oil yield and quality, develop resistance to various biotic and abiotic stresses, and adapt the crop to contemporary agricultural systems, including the implementation of mechanized harvesting. Furthermore, addressing inherent challenges such as the presence of toxic compounds like ricin and allergens remains a critical focus for castor breeding.

This report seeks to provide a comprehensive analysis of castor breeding, encompassing its fundamental principles and practices, the array of breeding methods employed, the primary objectives guiding breeding programs, the key traits that breeders focus on, the challenges and limitations encountered, and the recent advancements and innovations shaping the future of castor improvement.

2. Principles and Practices of Castor Breeding

2.1 Reproductive Biology of Castor

Castor predominantly relies on cross-pollination, with wind acting as the primary agent for pollen transfer [3]. Insects also contribute to pollination to a lesser extent [3]. Under natural conditions, the rate of cross-pollination can exceed 80%, indicating a strong tendency for outcrossing [5]. However, the plant possesses the capability for self-pollination if physical isolation is ensured, a technique sometimes employed in breeding for specific purposes [20]. The predominantly cross-pollinated nature of castor necessitates careful consideration of isolation distances during seed production to maintain genetic purity, particularly in the development and maintenance of parental lines for hybrid breeding [3].

The floral morphology of castor is characterized by the presence of unisexual flowers borne on racemes, exhibiting diverse sex expression patterns [3]. These patterns include monoecious spikes, where male flowers are located at the basal portion and female flowers at the apex; pistillate spikes, which consist entirely of female flowers; interspersed staminate flowers (ISF), where male flowers are distributed throughout the spike; and revertant spikes, which initially display female flowers but transition to monoecious in subsequent orders [3]. The proportion of male and female flowers on a given inflorescence is influenced by both the genetic makeup of the plant and prevailing environmental conditions [5]. Notably, temperature plays a significant role, with moderate temperatures favoring female flower development and higher temperatures promoting male flowers [5]. Additionally, nutritional status, particularly the availability of nitrogen, and the age of the plant can affect sex expression [3]. The complex and environmentally sensitive nature of sex expression in castor is a critical factor that breeders must carefully manage, especially in the context of hybrid seed production, which depends on the availability of stable pistillate lines for controlled pollination [3].

Castor seeds are typically ellipsoid in shape, featuring a mottled and shiny seed coat and a distinct caruncle, a small outgrowth at the base that aids in water absorption during germination [5]. The germination process in castor is epigeal, meaning the cotyledons emerge above the ground [5]. The duration from seedling emergence to the full maturity of the capsules containing the seeds varies depending on the genotype, generally ranging from 140 to 160 days [17].

2.2 Genetic Resources and Diversity

Historically, castor breeding programs have primarily utilized the genetic variability present within the primary gene pool of Ricinus communis [4]. While considerable progress has been achieved through the exploitation of this inherent variation, limitations exist, particularly in enhancing resistance to biotic stresses and improving certain aspects of oil quality, where the available genetic diversity has been reported as low [4]. This reliance on a potentially restricted genetic base underscores the necessity for breeders to explore alternative avenues for introducing new genetic variation into cultivated castor.

Studies employing various molecular markers, such as Simple Sequence Repeats (SSRs), Single Nucleotide Polymorphisms (SNPs), Random Amplified Polymorphic DNA (RAPD), and Inter Simple Sequence Repeats (ISSRs), have consistently indicated a narrow genetic base among cultivated castor varieties across the globe, including in China and within worldwide germplasm collections [6]. These analyses suggest a relative lack of distinct geographically structured populations within cultivated castor, implying that the phenotypic variation observed might not solely be attributable to extensive genetic diversity at the molecular level [23]. This limited genetic diversity presents a significant hurdle for breeding programs striving for substantial advancements in complex traits such as yield, tolerance to environmental stresses, and resistance to diseases and pests. Consequently, there is a growing recognition of the importance of introducing novel genetic resources into cultivated castor, either from wild relatives or through the application of techniques like mutagenesis and genetic engineering, to broaden the genetic base and unlock further potential for crop improvement.

The establishment and thorough characterization of germplasm collections are fundamental to the success of castor breeding programs [29]. These collections, encompassing both native and introduced varieties, as well as wild relatives, serve as the primary source of genetic diversity for breeders [1]. Detailed morphological and agronomic characterization of accessions within these collections is crucial for accurately assessing the genetic potential of the available resources and for identifying specific genotypes that possess desirable traits [2]. Maintaining a broad and well-characterized germplasm collection, which includes accessions exhibiting traits such as stable pistillate lines, resistance to prevalent diseases, high oil content, and non-shattering capsules, is essential for providing breeders with the necessary building blocks for developing improved castor varieties and hybrids [1].

2.3 Principles of Breeding

A fundamental principle in plant breeding is the understanding and application of heritability and genetic advance. Heritability quantifies the proportion of phenotypic variation in a population that is attributable to genetic differences among individuals, while genetic advance estimates the expected improvement in a trait in the next generation following selection. Studies on castor have revealed high heritability for several key agro-morphological traits, including seed yield per plant, plant height, 100-seed weight, effective primary spike length, and the number of capsules on primary spikes [31]. This high heritability indicates that a significant portion of the observed variation in these traits is genetically determined, suggesting that selection for these characteristics is likely to be effective in achieving genetic improvement.

Another crucial principle exploited in castor breeding is heterosis, also known as hybrid vigor. Heterosis refers to the phenomenon where the offspring of a cross between genetically distinct parents exhibit superior performance in one or more traits compared to either parent. In castor, hybrid breeding has become a major strategy for enhancing yield potential [3]. The primary approach for hybrid seed production in castor involves a two-line system, utilizing female (pistillate) lines that are incapable of self-pollination and male (monoecious or ISF) lines that provide the necessary pollen [3]. The process entails maintaining these parental lines separately and then crossing them under controlled conditions to produce hybrid seeds for commercial cultivation [3]. The development of the first commercially successful castor hybrid in India, GCH-3, demonstrated the power of heterosis by exhibiting an 88% increase in yield capacity compared to existing local varieties, highlighting the significant potential of this breeding strategy for enhancing castor productivity [15].

3. Breeding Methods for Castor Improvement

3.1 Hybridization in Castor

Hybridization is a cornerstone of castor breeding, primarily employing a two-line system for the production of high-yielding hybrids [3]. This system relies on the use of female (pistillate) lines, which possess only female flowers, and male (monoecious or interspersed staminate flower - ISF) lines, which provide the pollen source [3]. The process of hybrid seed production is typically carried out in two stages: the production of foundation seeds of the parental female and male lines, and the subsequent production of certified hybrid seeds for commercial use [3].

The maintenance of pure female lines, essential for hybrid seed production, is achieved through two primary methods: conventional and refined (or modified) [3]. The conventional method involves allowing up to 25% monoecious or revertant plants within the female line to serve as a pollen source for maintaining the pistillate character. However, this approach can lead to lower genetic purity and necessitates extensive roguing (removal of off-type plants) in the hybrid seed production plots [3]. The refined or modified method aims to overcome these limitations by maintaining pistillate lines during the summer season. Higher temperatures during this period can induce the expression of interspersed staminate flowers (ISFs) on the pistillate plants, which then self-pollinate the female flowers, thus eliminating the need for a separate maintainer line [3]. For certified hybrid seed production, a specific row ratio of female to male lines (typically 3-4:1) is maintained in the field, with male lines often planted around the borders to ensure a continuous and ample supply of pollen and to prevent contamination from external sources [3]. Maintaining an appropriate isolation distance, often revised to 300 meters, is crucial to prevent unwanted cross-pollination [3].

Successful hybridization also requires an understanding of the optimal conditions for pollination. Pollen viability is typically highest when temperatures are between 26°C and 29°C with a relative humidity of around 60% [18]. Stigma receptivity in female flowers can last for 5 to 10 days after opening, depending on environmental conditions [18]. In cases where controlled crosses are desired, manual pollination techniques are employed, involving the collection of viable pollen from the male parent and its transfer to the receptive stigma of the emasculated female flower, followed by bagging the inflorescence to prevent further pollination [18].

The development of superior hybrids often involves the creation and evaluation of inbred lines from diverse genetic backgrounds [34]. These inbred lines are then assessed for their combining ability, which refers to their performance when crossed with other inbred lines [40]. Hybridization can be carried out between different varieties (intervarietal) or even between different species (interspecific) to introduce novel traits [33]. Interspecific hybridization, while potentially valuable for expanding the genetic base, often faces challenges due to incompatibility barriers. Techniques like embryo rescue, involving the in vitro culture of fertilized ovules, can be employed to overcome post-fertilization barriers and recover viable hybrid progeny from such wide crosses [25].

3.2 Mutation Breeding in Castor

Mutation breeding is another significant approach employed in castor improvement, utilizing the induction of genetic mutations to create new allelic variants that can lead to desirable phenotypic expressions [25]. Mutations can be induced through physical mutagens, such as gamma rays and thermal neutrons, or chemical mutagens [25]. The use of mutation breeding in castor dates back to 1969 [25]. A well-known example of a successful mutant is NPH-1-Arun, a short-duration castor variety that matures in less than 120-150 days and possesses other desirable characteristics [25].

A systematic mutation breeding program initiated in 1988 at the Directorate of Oilseed Research (DOR), Hyderabad, India, aimed to incorporate wilt resistance into the susceptible castor line VP-1 [25]. Through gamma irradiation of VP-1 seeds, researchers identified several mutant lines that exhibited stable pistillate behavior and resistance to wilt under disease-prone conditions [25]. These mutants often displayed alterations in plant morphology in addition to wilt resistance, such as shorter internodes and changes in leaf and capsule characteristics [25]. One notable outcome of this program was the development of the hybrid DCS-591 (M-574 × DCS 78), released in 2006, which is an early-maturing, high-yielding hybrid with resistance to Fusarium wilt [25]. Mutation breeding has also been utilized to address other challenges, such as susceptibility to leafhoppers. By mutating the castor variety DPC-9 with gamma rays, researchers were able to select for mutants with improved leafhopper resistance, often associated with the presence of bloom on the stem and leaves [25]. The process of mutation breeding involves careful screening and selection of desirable mutants from the mutagenized populations over several generations to identify and stabilize the desired traits [42].

3.3 Selection Methods in Castor Breeding

Selection is a fundamental practice in castor breeding, aimed at identifying and propagating individuals with superior genotypes for desired traits [22]. Several selection methods are employed depending on the breeding objectives and the nature of the trait being selected. Mass selection is often used for traits that exhibit high heritability, where a large number of individuals are selected based on their phenotypic performance [33]. The seeds from these selected individuals are then bulked to form the next generation.

The pedigree method is a more systematic approach, particularly useful for developing improved inbred lines [23]. It involves selecting superior individuals in each generation and maintaining detailed records of their parentage, allowing breeders to track the inheritance of desirable traits and avoid inbreeding depression. Recurrent selection is employed for the gradual improvement of specific traits within a population [22]. This method involves selecting the best individuals from a population, intercrossing them, and then repeating the selection process over several cycles to progressively increase the frequency of favorable genes.

With advancements in molecular biology, marker-assisted selection (MAS) has become an increasingly important tool in castor breeding [12]. MAS utilizes molecular markers, such as SSRs and SNPs, that are linked to specific genes or quantitative trait loci (QTLs) controlling desirable traits like disease resistance or oil quality. By identifying the presence of these markers in young seedlings, breeders can select plants with the desired genetic makeup early in the breeding cycle, even before the phenotypic expression of the trait is evident, thereby accelerating the breeding process and increasing its efficiency [12]. For more complex traits controlled by many genes, genomic selection, which uses dense molecular marker profiles to predict the breeding value of individuals, is also being explored in castor breeding programs [25].

3.4 Other Modern Breeding Approaches in Castor

In addition to hybridization, mutation, and selection, several other modern breeding approaches are being utilized to enhance castor improvement. Polyploidy induction, often achieved through colchicine treatment, is employed to create plants with more than two sets of chromosomes [25]. Polyploid plants can exhibit increased biomass, larger organ size, and potentially enhanced tolerance to certain stresses [25]. Embryo rescue is a crucial technique used to overcome incompatibility barriers in distant hybridization, allowing breeders to obtain viable offspring from crosses that would otherwise fail [25].

Genetic transformation, involving the introduction of foreign genes into the castor genome, offers the potential to confer specific desirable traits that may not be available within the existing gene pool [4]. This can be achieved through methods like Agrobacterium-mediated transformation and particle gun bombardment, and has been used to introduce genes for insect resistance and potentially for reducing ricin content [4]. Tissue culture techniques play a supportive role in castor breeding by providing methods for rapid propagation of elite genotypes and for facilitating genetic transformation processes [4].

Finally, the integration of omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, is providing unprecedented insights into the molecular mechanisms underlying various traits in castor [23]. These approaches help in identifying genes associated with important traits, understanding gene regulation, and elucidating metabolic pathways, ultimately contributing to more targeted and efficient breeding strategies.

4. Environmental and Economic Benefits

A primary objective of castor breeding programs worldwide is to enhance oil yield [1]. This involves developing both high-yielding varieties and hybrids capable of producing a greater quantity of oil per unit area [1]. Strategies to achieve this include breeding for an increased number of racemes (flower clusters) and capsules (seed-bearing structures) per plant 1, as well as selecting for genotypes with higher seed weight, as this directly contributes to the overall yield [2].

Enhancing the quality of castor oil is another crucial objective [1]. This encompasses breeding for higher oil content within the seeds [1]. Furthermore, breeding programs aim to modify the fatty acid profile of the oil to meet specific industrial needs. This includes efforts to develop varieties with low ricinoleic acid content and very high oleic acid content [1]. Tailoring the fatty acid composition can broaden the range of applications for castor oil, potentially opening up new markets [1].

Improving the resistance of castor to various diseases and pests is a significant and ongoing objective [1]. Breeding programs focus on developing resistance to major diseases such as Fusarium wilt, root rot, charcoal rot, grey rot, bacterial leaf spot, powdery mildew, rust, and Alternaria [1]. Similarly, efforts are directed towards breeding for resistance to key insect pests, including the capsule borer, spodoptera, semi-looper, jassid, hopper burn, Heliothis, and grasshopper [1].

Developing desirable agronomic traits is also a crucial focus of castor breeding [1]. This includes breeding for short duration and early maturity varieties, allowing for more flexible cropping systems and potentially higher cropping intensity [1]. Developing non-shattering varieties is important to prevent seed loss before and during harvest, thereby maximizing yield [1]. Another significant objective is breeding for dwarf plant height and an architecture suitable for efficient mechanical harvesting, which is essential for modernizing castor production and reducing labor costs [10]. Enhancing drought tolerance and overall adaptability to diverse environmental conditions is also a key goal, particularly in regions prone to water scarcity [1]. Furthermore, breeding for low ricin content in the seeds is a critical objective to improve the safety of castor byproducts, such as castor cake, for potential use as animal feed and to enhance the overall value of the crop [1]. Finally, developing self-fertile lines can simplify seed production and potentially enhance yield stability in certain environments [33].

5. Key Traits Considered Important in Castor Breeding

Plant height and overall architecture are critical traits in castor breeding [2]. Breeders consider both dwarf and tall types, depending on the specific objectives. Dwarf types are generally preferred for ease of harvesting, especially with the increasing focus on mechanical harvesting [17]. The number of branches and the length of internodes (the segments between leaves on the stem) also influence plant architecture and are important considerations [2]. Developing varieties with an architecture suitable for mechanical harvesting, characterized by traits like dwarf internodes, fewer branches, erect stems, and long primary racemes, is a key target in modern breeding programs [10].

Seed size and weight are directly related to oil yield and are therefore important traits in castor breeding [2]. Generally, there is a positive correlation between seed weight and oil content, as well as overall yield [2]. Selection for larger and heavier seeds is a common strategy to improve productivity.

Oil content and quality are paramount in castor breeding [1]. Breeders aim to increase the percentage of oil extracted from the seeds [1]. Furthermore, the fatty acid composition of the oil is a key focus, with efforts to modify the proportions of different fatty acids, such as increasing oleic acid and decreasing ricinoleic acid, to enhance the oil's suitability for various industrial applications [1].

The maturity period, or the time taken for the crop to reach harvestable stage, is another important trait [17]. Breeding for short duration varieties is often desired to fit into specific cropping systems, allow for multiple cropping cycles within a year, and potentially escape unfavorable environmental conditions [23].

Resistance to various diseases and pests is a critical objective in castor breeding, and therefore resistance to specific diseases like wilt and root rot, as well as resistance to major pests such as capsule borers, are key traits under selection [1].

Other important traits considered in castor breeding include capsule dehiscence (shattering), which can lead to significant yield losses if seeds are dispersed before harvest [1]. Breeding for non-shattering varieties is therefore a priority. The content of ricin, a highly toxic protein found in castor seeds, is a major concern, and breeding programs aim to develop varieties with low or no ricin to improve safety and expand the utilization of castor byproducts [1]. Similarly, the presence of allergens in castor seeds poses a health hazard, and efforts are underway to breed varieties with reduced allergen content [13]. Tolerance to abiotic stresses, such as drought and salinity, is increasingly important, especially in regions facing environmental challenges, and is a key focus of breeding programs [1]. Finally, the stability of sex expression, particularly the reliable maintenance of pistillate lines for hybrid seed production, is a critical trait for successful breeding programs [3].

6. Challenges and Limitations Associated with Castor Breeding

One of the primary challenges in castor breeding is the narrow genetic base observed in cultivated varieties [4]. This limited genetic diversity restricts the availability of variability for key traits, making it difficult to achieve substantial improvements in yield, stress tolerance, and oil quality through conventional breeding methods alone [4]. Furthermore, molecular marker studies have indicated a lack of distinct geographically structured genetic populations in cultivated castor, suggesting that the existing diversity might not be readily accessible for targeted breeding [23].

The complex sex expression in castor presents another significant challenge [3]. The environmental sensitivity and instability of pistillate lines, which are crucial for hybrid seed production, can lead to unreliable seed yields and necessitate extensive roguing to maintain genetic purity [3]. Reversion in pistillate lines, where female plants start producing male flowers, further complicates seed production and reduces both the quantity and quality of hybrid seeds [3]. The underlying genetic mechanisms controlling pistillate traits are not fully understood, which hinders efforts to develop more stable and reliable female lines [24].

The presence of toxic compounds, specifically ricin and allergens, in castor seeds poses significant limitations [5]. These compounds raise safety concerns during the handling and processing of castor beans [16]. The toxicity of castor cake, a byproduct of oil extraction, restricts its use as animal feed, limiting its economic value [4].

Castor cultivation is also challenged by its susceptibility to various biotic and abiotic stresses [1]. The crop is vulnerable to a range of insect pests and diseases, which can cause significant yield losses [4]. Additionally, the increasing impact of climate change, including more frequent and severe droughts, erratic rainfall patterns, and temperature fluctuations, poses a growing threat to castor productivity [59].

While modern breeding approaches offer promising solutions, they also come with their own set of challenges and limitations in castor [4]. Castor has been reported to be recalcitrant to tissue culture and genetic transformation, making it difficult to efficiently apply these techniques for crop improvement [4]. Genetic transformation experiments aimed at introducing desirable genes often suffer from low transformation frequencies, hindering the development of transgenic castor varieties [4]. The efficiency and cost-effectiveness of some modern techniques can also be a limiting factor, particularly for widespread application in breeding programs [47]. Furthermore, regulatory hurdles surrounding genetically modified organisms (GMOs) can pose challenges to the development and commercialization of genetically transformed castor varieties [47].

7. Recent Advancements and Innovations in Castor Breeding

Significant advancements have been made in understanding the castor genome and developing molecular markers, which are crucial for modern breeding [23]. The development of a chromosome-level genome assembly has provided a valuable resource for gene identification and mapping [53]. Researchers have successfully identified and applied various types of molecular markers, including SSRs, SNPs, AFLPs, RAPDs, SRAPs, TRAPs, SCoTs, and EST-SSRs, for diverse applications such as genetic diversity analysis, quantitative trait loci (QTL) mapping, and genome-wide association studies (GWAS) [23]. These studies have led to the discovery of candidate genes associated with important agronomic traits, including plant architecture, seed size, oil content, and resistance to diseases and abiotic stresses [23].

Innovations in genetic transformation techniques have also been reported [4]. Protocols for stable genetic transformation of castor have been developed, albeit sometimes with low efficiency [50]. Significant efforts are underway to develop ricin-free and allergen-free castor varieties through genetic engineering approaches, aiming to overcome the safety concerns associated with this crop [4]. Genetic engineering is also being explored to modify oil production, such as engineering castor plants to produce epoxy oil or oil with very high oleic acid content, potentially expanding its industrial applications [1]. Furthermore, genes for resistance to both biotic (e.g., insect pests and diseases) and abiotic (e.g., drought, salinity) stresses have been introduced into castor through genetic transformation [25].

The integration of omics technologies is providing deeper insights into the complex biology of castor [23]. Transcriptomic and proteomic studies are being used to understand gene regulation and the molecular mechanisms underlying stress responses and development [23]. Metabolomic analyses are helping to elucidate the intricate pathways involved in oil biosynthesis and the accumulation of other important metabolites [23].

These advancements have contributed to the development of improved castor varieties and hybrids with enhanced traits [1]. These include high-yielding hybrids with improved resistance to diseases like Fusarium wilt and root rot 15, as well as varieties bred for dwarf plant height and other characteristics suitable for mechanical harvesting [10]. Efforts have also focused on developing climate-resilient genotypes with enhanced drought tolerance, crucial for sustainable production in many castor-growing regions [1]. Furthermore, varieties with improved oil quality, such as those with higher oil content and modified fatty acid profiles, are being developed to meet specific market demands [1].

Finally, there is an increasing emphasis on sustainable breeding practices in castor [59]. This includes a focus on developing varieties that are resource-efficient, require reduced reliance on chemical fertilizers and pesticides, and are adapted to climate change scenarios [59].

8. Conclusion and Future Outlook

Castor breeding has made significant strides through the integration of both conventional and modern breeding approaches. While traditional methods like hybridization and selection have been instrumental in developing high-yielding varieties, the application of modern techniques such as mutation breeding, marker-assisted selection, genetic transformation, and omics technologies is accelerating the pace of improvement. The narrow genetic base in cultivated castor remains a key challenge, highlighting the need for continued exploration of genetic diversity and the utilization of underutilized germplasm resources.

Future research priorities should focus on enhancing the efficiency of genetic transformation and gene editing technologies to precisely modify the castor genome for traits like ricin and allergen reduction, improved oil quality, and enhanced stress tolerance [25]. Developing robust and reliable molecular markers for key agronomic traits will further enhance the efficiency of breeding programs [23]. Breeding for climate resilience, particularly drought tolerance, will be crucial for ensuring the sustainability of castor production in the face of changing environmental conditions [1]. Continued efforts to address the challenges associated with ricin and allergen content through both breeding and biotechnology are essential for expanding the utilization of castor and its byproducts [1]. Promoting greater collaboration between academic research institutions and commercial breeding programs can help to translate research findings into practical applications more effectively [47]. Finally, developing optimized agronomic protocols tailored for modern, high-tech agriculture and mechanical harvesting will be critical for improving the efficiency and scalability of castor production [47].

Table 1. Basic Sex Expression Forms in Castor

Sex Expression Form	**Description of Flower Arrangement on the Spike**	**Influencing Environmental Factors**
Monoecious	Male flowers at the base, female flowers at the top	
Pistillate	Entirely female flowers	Winter, low temperature (<30°C), young plants, high nutrition (especially nitrogen) [3]
Interspersed Staminate Flowers (ISF)	Male flowers scattered throughout the spike	Summer, high temperature (>32°C), older plants, low nutrition (especially nitrogen) [3]
Revertant	Pistillate spike reverting to monoecious in later orders	

Table 2. Examples of Castor Varieties and Hybrids Developed for Specific Traits

Variety/Hybrid Name	**Key Trait Improved**	**Breeding Method Used**	**Source/Reference**
NPH-1-Arun	Short duration	Mutation breeding	25
DCS-591	Wilt resistance, early maturity	Mutation breeding, Hybridization	25

GCH-3	High yield	Hybridization	15
TMV 5	Insect resistance (triple bloom)	Hybridization, Selection	33
Baker	Non-shattering	Selection	33

Table 3. Key Agro-Morphological Traits in Castor and Their Heritability

Trait	**Heritability**	**Genetic Advance**	**Snippet IDs**
Seed yield per plant	High	High	31
Plant height	High	High	31
100-seed weight	High	High	31
Effective primary spike length	High	High	31
Number of capsules on primary spikes	High	High	31
Total length of primary spike	High	High	31
Days to maturity of primary spike	High	High	31
Percent oil content	High	High	31

Table 4. Molecular Markers Used in Castor Breeding and Their Applications

Marker Type	Application	Advantages	Limitations
SSR	Diversity analysis, QTL mapping, Purity testing	Co-dominant, multi-allelic, highly reproducible, polymorphic, locus-specific	
SNP	Diversity analysis, QTL mapping, GWAS	Abundant, potential for high-throughput genotyping, identification of conserved SNPs	
RAPD	Diversity analysis, QTL mapping	Low cost, no prior sequence knowledge required	Dominant markers (cannot distinguish heterozygotes), reproducibility can be an issue, may target non-coding regions [66]
AFLP	Diversity analysis	High number of informative marker bands	Dominant markers, technically demanding
SRAP	Diversity analysis	Targets gene-rich regions (Open Reading Frames), no prior sequence knowledge required	
ISSR	Diversity analysis	No prior sequence knowledge required	Dominant markers
TRAP	Genetic divergence studies	Targets specific regions	
SCoT	Diversity analysis	Targets start codon regions	Lower percentage of polymorphism compared to RAPD [67]
EST-SSR	Diversity analysis	Derived from expressed genes	May have lower polymorphism compared to genomic SSRs [28]
RFLP	Diversity analysis, QTL mapping	Co-dominant, highly reliable	Time-consuming, requires large amounts of high-quality DNA, lower throughput compared to PCR-based markers

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