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REVIEW ARTICLE

CYTOPLASMIC MALE STERILITY : A REVIEW ON ITS ROLE AS A GENETIC INNOVATION DRIVING HYBRID BREEDING AND CROP IMPROVEMENT

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ABSTRACT

Cytoplasmic male sterility (CMS), a maternal-effect inheritance, refers to a plant's inability to produce fertile pollen, which is caused by disharmony between nuclear and mitochondrial genes. CMS normally results in sterile male reproductive organs in the plant, which can be overcome by restorer of fertility (Rf) genes. This review integrates current information on CMS systems, their genetic mechanisms, origins, importance, and applications in major crops like rice, wheat, maize, sunflower, and onion from comprehensive scientific literature. In spite of its known advantages, CMS presents certain drawbacks and genetic instability, which the review discusses. Some of the most efficacious CMS systems—for example, PET-1 in sunflower and CMS-WA in rice—have been found to facilitate stable sterility along with efficient fertility restoration. Therefore, such varieties have opened gateways toward genetically pure hybrid seeds that yield more, possess better disease resistance, and have greater stress tolerance. However, challenges still exist. CMS-based crops can be genetically fragile, and the limited diversity of CMS sources threatens long-term breeding achievements. Besides just raising yields, CMS has streamlined breeding programs and improved some of the most important agronomic characteristics. Therefore, the future of breeding is expected to see the development of new CMS sources and their broader practical application to address global food security challenges.

KEYWORDS

Breeding, Cytoplasmic Male Sterility (CMS), Fertility restoration (Rf), Hybrid

1. INTRODUCTION

Male sterility (MS) is characterized by non-functional pollen grains, while female gametes function normally (Kaushik and Dhaliwal, 2018). The contribution of this system in combating global hunger through its use in developing high-yielding hybrids in various food crops has been immense (Bohra et al., 2016). The state in which a plant's male reproductive organs are absent, aborted, or nonfunctional is known as male sterility. As a result, they are unable to engage in the process of sexual reproduction. This situation can arise due to any developmental defect at any stage of microsporogenesis or the release of pollen grains (Chen and Liu, 2014). The first report on the occurrence of male sterility was presented by German botanist Joseph Gottlieb Kolreuter in 1763. For this study, MS was defined as plant malfunction to produce dehiscent anthers, functional pollen (Xu et al., 2015). Male sterility is mainly of four types:

1.1 Genetic Male Sterility (GMS)

Nuclear genes govern GMS, which frequently involves a single recessive gene (ms). It has been observed in a variety of crops, including cabbage, tomato, and brinjal (Mishra and Kumari, 2018 ; Hazra et al., 2007). The requirement to maintain heterozygous conditions, which makes breeding programs more difficult, makes GMS less economically used (Patel et al., 2025).

1.2 Cytoplasmic genetic male sterility (CGMS)

Nuclear and cytoplasmic gene interactions are a part of CGMS. It has been effective in creating hybrids of crops like onions and chillies (Prasanth et al., 2014). This method offers flexibility in breeding tactics by combining the advantages of CMS and GMS (Patel et al., 2025).

1.3 Environment Sensitive Genetic Male Sterility (EGMS)

Environmental influences have an impact on EGMS, which offers a distinctive method of hybrid production. Although less prevalent, it has promise in particular environmental settings (Liu et al., 2022).

1.4 Cytoplasmic Male Sterility (CMS)

Nuclear restorer genes (Rf) can frequently reverse the mutations in the mitochondrial genome that cause cytoplasmic male sterility (CMS). It is extensively utilized in the creation of hybrid seeds for crops such as carrots and cabbage (Prasanth et al., 2014 ; Liu et al., 2022). CMS technologies simplify hybrid development by eliminating the need to maintain heterozygous conditions (Patel et al., 2025). Cytoplasmic male sterility (CMS) is a maternally inherited trait with mitochondrial mutations that lead to the non-production of functional pollen. CMS systems have been used as models to investigate male gamete development, fertilization and cytoplasmic effects on inheritance. The four-component assembly of male sterile mutant, fertility restorer line (A), sterility maintainer line (R) and environment modification through agricultural management has had a powerful perturbation for CMS system in agriculture as it economically exploits heterosis breeding advancement for several crops (Toriyama, 2021). More recently, a spontaneous CMS in a mutant line of the B. napus cultivar Xiangyu 13 (Liu et al., 2005).

2. MECHANISMS

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Several studies have shown that genes associated to cytoplasmic male sterility (CMS) are located within the mitochondrial genome and cause pollens impairment, whereas restorer fertility (Rf) genes, crucial for restoring fertility in F1 hybrids, originate from the nuclear genome (Tang et al., 2017; Budar et al., 2003). Different plants have different cytoplasmic male sterility mechanisms. According to certain researchers who have established the genetic basis of CMS, normal cytoplasm (male fertile) becomes ineffectual when pollen sterility is caused by an interaction between the male sterile cytoplasm and a homozygous recessive nuclear gene (Islam et al., 2014). Male sterility is often attributed to the programmed cell death of tapetum cells in mitochondrial-encoded CMS systems, and increasing the number of mitochondria will not be sufficient to ensure energy production during pollen formation (Baulk and Leaver, 2001). Ultimately, the central concept revolves around the imbalance between the mitochondrial and nuclear genomes, particularly driven by the expression of specific mitochondrial open reading frames (ORFs) genes (Zhang et al., 2022).

3. Sources Of Cms

Despite the widespread application of CMS lines in hybrid seed production, the origins of numerous CMS sources remain elusive. Three principal methods have been recognized for acquiring original CMS sources: spontaneous emergence in natural populations, distant hybridization, and somatic hybridization (Zhu, 2001). For instance, certain CMS types, such as WA-CMS in rice, have been disseminated to various sterile lines globally.

Distant hybridization is the predominant method for generating CMS sources, with notable examples including Honglian-type CMS and Boro II-type CMS in rice (Hu et al., 2012). In certain instances, CMS has been engineered through transgenic methods, such as the modulation of the nuclear gene Msh1 via RNA interference or the transfer of mitochondrial genes like orf 239 from beans to tobacco (He et al., 1996).

4. Significance Of Cms

4.1 Hybrid Seed

Seeds produced from cytoplasmic male sterility (CMS) are genetically pure compared to seeds produced through open pollination (Singh et al., 2023). In agriculture, hybrid seed is a vital resource for production enhancements; hybrid vigor or heterosis enhances the tolerating ability of the plant to abiotic and biotic challenges. Along with contributing to higher production, heterosis enables stress tolerance against low soil fertility, drought conditions pests, and diseases (Duvick, 2001). A study conducted on hybrid seed production in wheat (*Triticum aestivum* L.) also shows that the mean grain yield of the CMS-based hybrids was greater than that of the Chemical hybridizing agent (CHA)-based hybrids (Adugna et al., 2006). CMS hybrids exhibit a "female advantage" due to either enhanced female reproductive capacity resulting from resource allocation away from male functions or improved seed vitality by reducing self-pollination (Budar et al., 2003). The cost of emasculation for the manufacturing of hybrid seeds was eliminated by CMS. The CMS line is crossed with the nuclear fertility restorer line (Rf) for hybrid seed production. In hybrid seed production, the presence of fertility restorer genes is crucial. As a result, the discovery of restoration-of-fertility (Rf) genes in various crops has progressed at a rate similar to the discovery of sterile cytoplasm. It maintains the genomic equilibrium between cytoplasmic (mitochondrial and plastid genomes) and nuclear genomes and enables functional pollen production (Dahan and Mireau, 2013).

4.2 Enhance Agronomic Character and Yield Traits

CMS facilitates the development of improved varieties through controlled breeding. Agronomic features eventually improve as a result of it. CMS maize shows slow senescence of silk. The decelerated senescence of silk in CMS maize cultivars could extend the duration of pollen shedding, thereby augmenting the probability of effective pollination and subsequent seed development (Stamp et al., 2000). Consequently, this phenomenon has the potential to significantly enhance overall crop yield.

In the case of sunflower, hybrids produced from the cross of the CMS line (CMS-XA × P100R, CMS-ARG-2A × P100R) give better seed and CMS line CMS-E002-91A × P124R, CMS-E002-91A × P100R, and CMS-40A× P124R were the best combiners as for oil content as compared to conventional variety (Tyagi et al., 2018). In wheat (*Triticum aestivum* L.), lines with CMS showed nearly double the outcrossing percentage rate compared to lines treated with (CHA) chemical hybridizing agents (Singh et al., 2021). In comparison to both the CHA-treated lines, the weight of 1,000 grains weight of cross seeds in the CMS lines was higher. Viable crossbred seeds from CMS lines showed three times higher viability compared to CHA-treated lines, with double the average germination rate (Adugna et al., 2004). This shows the contribution of CMS in enhancing the agronomic trait of crops as compared to that of chemically hybridized crop lines.

4.3 Control Pollination

Before the middle of the 20th century, emasculation was essential for producing hybrid seeds in self-pollinating plants to prevent self-pollination. However, this process required manual labor, machinery, or chemical treatments, making it expensive, inefficient, and potentially harmful to the environment. The development of CMS technology has overcome the problems of emasculation and self-pollination (Chen and Liu, 2014). Cytoplasmic Male Sterility is an effective tool to control self-fertilization and allow breeders to enhance hybridization and increase productivity (Singh et al., 2015). In the case of Brassicaceae, natural sporophytic self-incompatibility (SI) has been replaced by the cytoplasmic genetic male sterility (CGMS) to control pollination and hybrid production because of the occurrence of self-pollination in some cases (Singh et al., 2013).

4.4 Disease Resistance

The parental line CMS E002-92, R-5, and R-77-2 III of Sunflower (*Helianthus annuus* L.) were found to be resistant to powdery mildew caused by *Erysiphe cichoracearum* (Nandini et al., 2016). According to Saxena and Sharma (2018), the world's first CMS-based legume hybrid, ICPH 2671, is resistant to sterility mosaic disease and wilt. *S. stoloniferum* (W/γ- CMS) and *S. demissum* (DCMS) were obtained from maternal parental accessions of Mexican polyploid species which are widely used in the breeding program as a source of resistance for the Late blight caused by (*Phytopthora infestans*) and Potato virus Y (Sanetomo and Gebhardt, 2015). CMS aids in facilitating the incorporation of disease-resistance traits into crops; R1-CMS provides pollen control, streamlining the incorporation of disease-resistant genes through backcrossing CMS plants with recurrent plants. This idea has been included into CMS *Brassica campestris* L. germplasms, making them resistant to Clubroot, Downy mildew, and Turnip Mosaic Virus (TMV) (Leung and Williams, 2022). Through the implementation of Marker-Assisted Selection (MAS), resistance to Bacterial Leaf Blight (BLB) has been incorporated into the parental line (Pusa Sugandh 2×CMS Line Pusa 6A) of Pusa RH10 (Basavaraj et al., 2010).

However, with the scarcity of CMS lines, diversification of both CMS and inbreeding lines is pivotal through diverse crossing programs to mitigate genetic risks associated with reliance on a single cytoplasm. This diversity helps prevent vulnerability to specific stresses, reducing the potential for outbreaks of epidemic diseases.

4.5 Simplified Breeding System

With modern techniques like cytoplasmic male sterility (CMS), the breeding system has undergone significant modification and become more straightforward. Since the primary goal of forage plant breeding is biomass production, cytoplasmic male sterility has a lot of potential for forage plants, and even the expense of fertility restoration is not necessary (Ruge et al., 2003). Gahi-3 (Tift 23DA1 × Tift 186) was the 1st CMS-based forage hybrid released in 1972 A.D. following the identification of pearl millet's A1 CMS (Serba et al., 2017). However, as the breeding system prioritizes increasing biomass, there are consequential loss of seeds, leading to the imminent extinction of landrace varieties. Because of its significant advantages, including total pollen abortion and a high progeny sterility rate of up to 100%, ogura CMS is widely used in cruciferous crop breeding (Ren et al., 2022). For crops where seed production doesn't play a vital role, CMS-based breeding can be quite effective for that process. In cauliflower (*Brassica oleracea var. botrytis*) it is not necessary to maintain a restorer line (Rf) because the curd (intermediate stage) in this situation is an edible component (Kumar et al., 2020). Therefore, for the hybrid growth of cauliflower, the cytoplasmic male sterility mechanism is most effective. CMS makes breeding easier by providing hybrid seeds in self-pollinating crops, saving money on emasculation and reducing the time needed for good yields.

5. Application Of Cms In Different Crops

5.1 CMS in Rice

CMS/Rf techniques exclude the need of hand emasculation; hence, it is crucial in commercial hybrid seed production. Several mitochondrial genes that are accountable for CMS can be concealed by effect of one or more nuclear genes known as restorer-of-fertility genes (Hanson and

Bentolina, 2004). Basically, in rice there are three CMS/Rf systems known as CMS-BT, CMS-WA and CMS-HL.

CMS-BT: This is completely recognized system of CMS in rice. In BT type CMS, cytoplasm extracted from Chinsurah Boro II induces MS when paired with nucleus from rice line Taichung 65 that bears no restorer gene (Shinjyo, 1969). A chimeric gene called orf79 in mitochondrial genome of Chinsurah Boro II which codes for cytotoxic peptide was detected to be causing agent for gametophytic MS by transgenic experiments (Wang et al., 2006b).

CMS-HL: By recurrent backcrossing of red awned wild rice (Oryza rufipogon) from Hanian, China with indica variety Lian-Tang-Zao, CMS-HL line of rice was produced. Hybrids from CMS-HL system have been majorly grown in China as compared to rest of CMS system (Liu et al., 2004). In this system of CMS, expression of orf79 triggers the pollen abortion and nuclear Rf gene can restore fertility (Peng et al., 2010). Wen et al., 2010; Sun et al., 2009 advised that reducing level of energy production i.e., ATP played a significant role in causing CMS-HL by procurement of orf79 in mitochondria degrades normal functioning i.e., energy production protein was decreased in anther causing CMS-HL.

CMS-WA: WA-CMS; wild abortive CMS is acquired from wild species Oryza rufipogon, which is the most common for hybrid seed production (Lian and Yuan, 1980). This type of CMS reveals uniqueness in genetic and cytological form differing from CMS-BT and CMS-HL. Here, pollen gets aborted earlier at uninucleate stage and aborted pollen are unstructured. This creates sporophytic male sterile unlike from CMS-BT and CMS-HL which forms gametophytic (Saxena et al., 2010). Recently, it is suggested that orf126 is the CMS related gene on the basis of comparison of mitochondrial genomes through next gene sequencing (Bentolina and Stefanov, 2012).

5.2 CMS in Wheat

Hybrid wheat has the potential to significantly increase yields to meet future food demands (Foley et al., 2011). However, developing an efficient male sterility system for hybrid seed production remains challenging (Tang et al., 2021). Several approaches have been explored, including cytoplasmic male sterility (CMS), chemical hybridizing agents (CHAs), and nuclear genetic male sterility (NGMS). CMS systems face issues with fertility restoration and undesirable pleiotropic effects, CHAs can be phytotoxic, and their efficacy is environmentally sensitive (Farooq et al., 2023). NGMS systems like thermo-sensitive genetic male sterility (TGMS) show promise but are also affected by environmental fluctuations (Li et al., 2006). However, developing an efficient male sterility system for hybrid seed production remains challenging (Tang et al., 2021).

Although many attempts have been made nearly for a century to improve the efficiency in the breeding of wheat using the system of hybrid breeding, the process has not gained much significance. A consistent and reliable sterility system is needed to further hybrid breeding programs. For hybrid seed breeding, it is necessary to reduce self-pollination, which can be done through mechanical methods such as emasculation or chemicals and genetics such as nuclear and cytoplasmic MS (Chen and Liu 2014). Another problem with wheat is that since wheat is autogamous, mechanical emasculations are out of the question in this crop because this process is time-consuming, laborious, and expensive as well. Later in 1950, Naylor came up with chemical hybridization agents (CHAs) as the method of encouraging male sterility. However, these agents posed a high threat to plant health and continued to lead to the death of both male and female plants due to the toxicity implication of the product by (Gowda et al., 2012) and (Longin 2016). CMS has been proven very effective in achieving significant breakthroughs in the production of commercial hybrids in crops like maize, rice, oilseed grape, and several others (Wan et al., 2019 ; Prat et al., 2002).

The benefits of nuclear genetic male sterility (NGMS), which was first applied to wheat in 1959, include avoiding the negative effects of cytoplasmic and alloplasmic interactions, being highly stable, insensitive to environmental changes, and not having any toxic effects on other traits (Farooq et al., 2023). The phenomena of gametophytic male sterility (GMS) genes remain vital for wheat improvement; the functional validation as well as application of these genes in hybridization systems is limited. To overcome this challenge, therefore, Farooq et al. (2023) have suggested the different measures. Using these approaches, it may be possible to find and describe novel useful GMS genes that have not been studied so far. This may open the doors to an increase in the yields of wheat hybrid seeds, which may lead to the second green revolution. The CMS approach for sterility control for hybrid wheat development is discussed below:

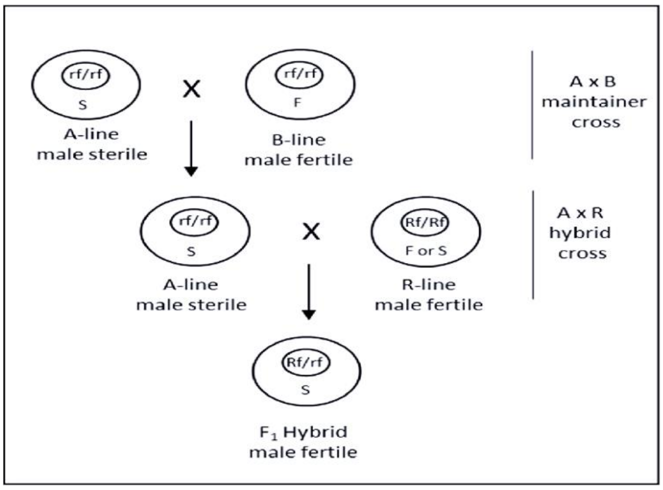

Figure 1: Hybrid wheat development (Singh et al., 2021)

A typical CMS system comprises a cytoplasmic male-sterile line, a restorer line containing the Rf gene (which is essential for generating F1 hybrid seeds), and a maintainer line that preserves the CMS line. The hybrid seed production process involves two stages of cross-pollination, with the Rf genes responsible for restoring fertility derived from the same species that provides the cytoplasm (Hu et al., 2012; Wang et al., 2006).

The nucleus of *T. aestivum* has been paired with cytoplasm from various related species to investigate CMS. During the late 1970s and 1990s, several hybrid varieties were commercialized utilizing the *T. timopheevii* as CMS line (serving as the egg source) alongside *T. aestivum* (providing pollen) within the T-CMS framework. At that time, *T. timopheevii* Zhuk was regarded as the most suitable option for commercial hybrid seed production due to its consistent male sterility, a wealth of recessive alleles, and a high degree of dominance (Rice et al., 2000). Nevertheless, the cytoplasm of *T. timopheevii* was associated with several undesirable pleiotropic effects, such as shriveled grains (Whitford et al., 2013).

5.3 CMS in Onion

5.3.1 Development of onion hybrid

- Using male sterility : Hisar onion 2 variety can be used for selecting male sterile line where as Hisar onion 3, Pusa Red and Agri-found Dark Red can be used as tester to develop hybrid (Singh and Khar, 2021). For the development of onion hybrid seeds, following steps are listed:

- Isolation and maintenance of MS line : Through morphological evaluation by hand touching method, screening for male sterility is done in Hisar 2 variety. Pollen viability is then evaluated under 0.5% acetocarmine solution. Viable pollen under this test gives off pink color and sterile being colorless and shrinked. Flower umbel of MS plants are selected and paired with umbel of male fertile for hybrid development. Paired umbels which need to be covered by muslin bag are shaken each morning for pollination. Then seeds from MS line and MF fertile lines are harvested individually for coming planting (Dehghani et al., 2021).

- Recognition and maintenance of maintainer line : Stocks bred from previous seed is now screened to ensure MS. F1 generation and its pollen parent are grown separately and at the period of dehiscence, each plant are morphologically checked for fertile and sterile condition based on presence of pollen in anther by touching with hand. Plant revealing greenish yellow or yellowish brown or yellow pollen being allocated as fertile and ones without pollen on sterile. Then only sterility of pollen is assured under microscope with acetocarmine solution. Stocks raised are now classified on the basis of proportion of male sterile and fertile division. According to research conducted in Haryana, India among 95 crosses only 8 crosses showed 100% sterile plant (Singh and Khar, 2021). Then, seed of maintainer, fertility restorer and parental hybrid lines are carried separately and preserved.

- Using molecular marker assisted selection for CMS : For open pollinated varieties (OPVs), use of cytochrome-b (cob) protein as mitochondrial DNA marker as well as phenotypic evaluation was conducted by Manjunathagowda (2021) to validate selection of male sterile and maintainer lines. Ahmad et al., (2020) recognized locus for fertility restorer by help of 2 sets of nuclear markers; MK marker, (orf 725 gene) and SCAR marker for ms and MS alleles among OPVs.

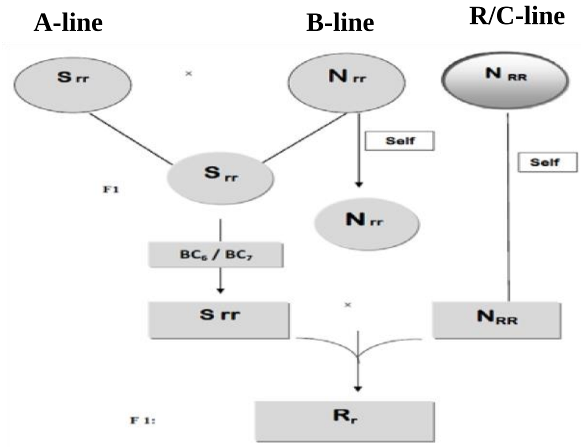

Figure 2: Steps involved in development of onion hybrids using CMS system (Mohsin et al., 2016).

5.4 CMS in Mustard

For the efficient hybrid production of *B. juncea*, pollination control mechanism is must which makes CMS as a suitable alternative. CMS system such as spontaneous CMS like 'Pollima' in B. napus is devoid of human manipulation (Sodhi, Y.S. et al., 2006).

Numerous CMS in *B. juncea* has been developed by breeding it with next sp. Like *B. oxyrrhina, B. toumefortii* etc. yet these revealed problems such as abnormality in growth, incapable of fertility restoration (Prakash et al., 2001). Still, this can be fixed by introducing fertility restorer genes but this process faced challenges i.e., some plants gained male fertility however they show some unwanted traits like changed leaf shape, seed types etc. In some plant fertility was restored partially, but problems like abnormal growth, reduced female fertility is seen (Kirti et al., 1993). The CMS system called '126-1' explored in *B. napus* successfully relocated to *B. juncea* by crossbreeding for its potential in robust hybrid seed production (Sodhi et al., 2006).

5.5 CMS in Sunflower

Among the CMS types, PET-1, derived from *Helianthus petiolaris,* is the most widely used source globally due to its stable expression and adaptability. Other CMS sources like CMS I from *H. lenticularis* and CMS PEF from *H. petiolaris ssp. fallax* has also shown potential, providing genetic diversity and resilience in sunflower breeding programs (Gouri Shankar et al., 2007). The CMS-restorer system eliminates manual emasculation, significantly improving hybrid seed purity and production efficiency. Recent advancements, including molecular markers and genomic tools, offer new avenues for enhancing CMS-based hybrid breeding and addressing challenges like biotic and abiotic stresses (Gouri Shankar et al., 2007). Diversification and innovation in CMS exploitation remain crucial for sustainable and resilient sunflower hybrid seed production systems.

Table 1 : Examples of CMS-Rf genetic systems in plant crop species

Species	Type of CMS	Mitochondrial gene	Rf gene	Product of Rf gene	Function of protein encoded by Rf gene	Reference
Oryza sativa	BT	*atp6-orf79*	*Rf1*	PPR	mRNA processing	Wang et al., 2006
	LD	*orf79*	*Rf2*	Glycine-rich mitochondrial protein	mRNA processing	Itabishi et al., 2011
	HL	*orf79*	*Rf5*	PPR	Processing of *atp6-orf79* transcript	Hu et al., 2012
	CW	Unknown	*Rf7*	Mitochondrial protein containing part of synthase-like domain of acyl carrier protein	Participation in retrograde signaling	Fuji and Toriyama, 2009
Triticum aestivum	K	*orf256*	*Rfv2*	Not identified	Unknown	Song et al., 2014
Solanum tuberosum	T/beta	*atp6*	*Rt*	Not identified	Restores pollen fertility in hybrids	Iwanaga et al., 1991
Allium cepa	S	*orf725*	*Ms*	Pentatricopeptide repeat (PPR)	mRNA processing and pollen fertility restoration	Sato, 1998
Helianthus annuus	PET1	*orfH522*	*Rf1, Rf2*	Not identified	Unknown	de la Canal et al., 2001; Horn, 2006

5.6 CMS Limitation

The capacity of a CMS system to preserve male sterility consistently across many genetic backgrounds and environmental conditions is critical to its commercial viability (Yadav and Rai, 2013). The relationship between genetics and environmental factors in CMS-based hybrid development requires further study. Environmental factors that impact CMS fertility stability include high humidity in pearl millet, low temperatures during panicle development stage in maize and pigeon pea, and scorching temperatures of 42°C and higher in sorghum (Reddy et al., 2004). Not every crop species has genes for fertility restoration by nature. There aren't many options for genes that restore fertility in different crops (Liu et al., 2002), which makes it harder to test for powerful heterosis combinations (Guo et al., 2006). The only fertility restoration (Rf1) genes currently utilized in commercial hybrid seed production in sunflowers are PET1 (CMS Source) and Rf1, which leads to a lack of genetic diversity that leaves commercial sunflower seed production vulnerable to diseases and environmental stresses (Talukder et al., 2019). The parental lines should be maintained as genetically pure as feasible for CMS hybrid formation (Saxena and Sharma, 2018). The flower of the cytoplasmic sterile parent must either draw pollen vectors or have extremely sticky stigmas in order to capture wind-borne pollen for fertilization if it lacks a fertility restorer gene. Despite the development of CMS soybean hybrids, large-scale hybrid seed production is inadequate due to poor pollen movement from the male to the female makes production challenging (Palmer et al., 2011). Commercial CMS hybrids are more prone to ergot than pollinated varieties because the lack of pollen causes a longer flower opening duration. The fungus Claviceps specifically prevents pollen tubes from developing through the stigma (Tenberge, 1999). However, CMS has bright future potential in plant breeding.

6. Conclusion

Cytoplasmic male sterility (CMS) has transformed plant breeding from a labor-intensive craft into a precision system for producing vigorous, genetically pure hybrids across cereals, oilseeds, and vegetables. It has boosted crop yields, improved resistance to disease making agriculture more productive. Over-reliance on a narrow set of cytoplasm and restorer sources can create genetic vulnerability; some CMS systems still carry pleiotropic penalties or environment-sensitive restoration; and in a few crops, reliable restoration remains the bottleneck to full commercial adoption. To overcome these and create truly reliable hybrid seed systems, the solution lies in cross- cutting approaches like integrating CMS with omics and gene editing technologies. Fusion of plant breeding with biotechnology provides immense opportunities to transform recent agricultural practices and ensure sustainable food security in the face of escalating global challenges.

References

Adugna, A., Nanda, G. S., Singh, K., and Bains, N. S. 2004. A comparison of cytoplasmic and chemically-induced male sterility systems for hybrid seed production in wheat (Triticum aestivum L.). Euphytica, 135(3), Pp. 297–304.

Adugna, A., Nanda, G.S., and Bains, N.S., 2006. A comparison of cytoplasmic and chemically-induced male sterility systems for hybrid performance in wheat (Triticum aestivum L.). Acta Agronomica Hungarica, 54 (1), Pp. 109–120.

Ahmad, R., Hassand, MU., Akhtar, GB., Saeed, S., Khan, SA., Shah, MKN., and Khan, N. 2020. Identification and characterization of important sterile and maintainer lines from various genotypes for advanced breeding programmes of onion (Allium cepa L). Plant Breeding, 139, Pp. 988–995.

Balk, J., and Leaver, C.J. 2001. The PET1-CMS mitochondrial mutation in sunflowers is associated with premature programmed cell death and cytochrome c release. The Plant Cell, 13 (8), Pp. 1803–1818.

Basavaraj, S.H., Singh, V.K., Singh, A., Singh, A., Singh, A., Anand, D., Yadav, S., Ellur, R. K., Singh, D., and Gopala Krishnan, S. 2010. Marker assisted improvement of bacterial blight resistance in parental lines of Pusa RH10, a superfine grain aromatic rice hybrid. Molecular Breeding, 26, Pp. 293–305.

Bentolila, S., and Stefanov, S. 2012. A reevaluation of rice mitochondrial evolution based on the complete sequence of male-fertile and male sterile mitochondrial genomes. Plant Physiology. 158, Pp. 996–1017.

Bohra, A., Jha, U. C., Adhikari, S., Mandal, S., and Singh, I. P. 2016. Male sterility and its utilization in hybrid breeding: Opportunities and challenges. Plant Breeding Reviews, 39, Pp. 199–237.

Budar, F., Touzet, P., and De Paepe, R. 2003. The nucleo-mitochondrial conflict in cytoplasmic male sterilities revisited. Genetica, 117, Pp.3-16.

Chen, L., and Liu, Y.G. 2014. Male sterility and fertility restoration in crops. Annual Review of Plant Biology, 65, Pp. 579–606.

Dahan, J., and Mireau, H. 2013. The Rf and Rf-like PPR in higher plants, a fast-evolving subclass of PPR genes. RNA biology, 10 (9), Pp. 1469-1476.

de la Canal, L., Crouzillat, D., Quetier, F., and Ledoigt, G. 2001. A transcriptional alteration on the atp9 gene is associated with a sunflower male-sterile cytoplasm. Theoretical and Applied Genetics, 102(8), Pp. 1185–1189.

Duvick, D.N. 2001. Biotechnology in the 1930s: the development of hybrid maize. Nature Reviews Genetics, 2 (1), Pp. 69–74.

Farooq, A., Khan, U. M., Khan, M. A., Ali, Z., Maqbool, R., and Sajjad, M. 2023. Male sterility systems and their applications in hybrid wheat breeding. Cereal Research Communications, April.

Fujii, S., and Toriyama, K. 2009. Supressed expression of retrograde-regulated male sterility restores pollen fertility in cytoplasmic male sterile rice plants, Proceedings of the National Academy of Sciences, 106(23), Pp. 9513–9518.

Gouri Shankar, V., Ganesh, M., Ranganatha, S., Suman, A. R. G., and Sridhar, V. 2007. Combining ability studies in diverse CMS sources in sunflower (Helianthus annuus L.). Indian Journal of Agricultural Research, 41(3), Pp. 171–176.

Gowda, M., Friedrich, C., Longin, H., Lein, V., and Reif, JC. 2012. Relevance of specific versus general combining ability in winter wheat. Crop Science 52(6), Pp. 2494–2500.

Guo, R. X., Sun, D. F., Tan, Z. B., Rong, D. F., and Li, C. D. 2006. Two recessive genes controlling thermophotoperiod-sensitive male sterility in wheat. Theoretical and Applied Genetics, 112(7), Pp. 1271–1276.

Hanson, M. R., and Bentolila, S. 2004. Interactions of mitochondrial and nuclear genes that affect male gametophyte development. Plant Cell, 16(Suppl. 1), Pp. S154–S169.

Havey, M. J. 2004. The use of cytoplasmic male sterility for hybrid seed production. In H. Daniell and C. D. Chase (Eds.), Molecular biology and biotechnology of plant organelles: Chloroplasts and mitochondria Pp. 623–634. Springer Netherlands.

Hazra, P., Roy, T., Choudhury, J., and Atanassova, B. 2007. Male sterility in tomato (Lycopersicon esculentum Mill.) and brinjal (Solanum melongena). International Journal of Plant Breeding, 1(1), Pp. 41–50.

Horn, R. 2006. Recombination: Cytoplasmic male sterility and fertility restoration in higher plants. In Progress in Botany Vol. 67, Pp. 31–52.

Hu, J., Wang, K., Huang, W., Gai Liu, YA., Gao, JW., Huang, Qi., Ji, Y., Qin, X., and Wan, L. 2012. The rice pentatricopeptide repeat protein RF5 restores fertility in Hong–Lian cytoplasmic male-sterile lines via a complex with the glycine-rich protein GRP162. Plant Cell 24:109–122.

Islam, M. S., Studer, B., Møller, I. M., and Asp, T. 2014. Genetics and biology of cytoplasmic male sterility and its applications in forage and turfgrass breeding. Plant Breeding, 133(3), Pp. 299–312.

Iwanaga, M., Ortiz, R., Cipar, M. S., and Peloquin, S. J. 1991. A restorer gene for genetic-cytoplasmic male sterility in cultivated potatoes. American Potato Journal, 68, Pp. 19–28.

Kaushik, P., and Dhaliwal, M. S. 2018. Male sterility and its utilization in hybrid seed production. Plant Breeding Reviews, 42, Pp. 189–220.

Kumar, A., Kumar, A., and Roy, C. 2020. Advancement in CMS-based hybrid development in cauliflower (Brassica oleracea var. botrytis). International Journal of Plant and Soil Science, 32(15), Pp. 18–24.

Kumar, Y., Singh, R., and Khar, B. 2021. Development of hybrids and hybrid seed production of onion. ResearchGate.

Leung, H., and Williams, P. H. 2022. Cytoplasmic male sterile Brassica campestris breeding lines with resistance to clubroot, turnip mosaic, and downy mildew. HortScience, 18(5), Pp. 774–775.

Linke, B., and Börner, T. 2005. Mitochondrial effects on flower and pollen development. Mitochondrion, 5(6), Pp. 389–402.

Liu, C. G., Hou, N., Liu, G. Q., Wu, Y. W., Zhang, C. L., and Zhang, Y. 2002. Studies on fertility genes and its genetic characters in D2-type CMS lines of common wheat. Yi Chuan Xue Bao = Acta Genetica Sinica, 29(7), Pp. 638–645.

Liu, Q., Qi, J., Wu, J., and Ni, F. 2022. Identification of wheat male sterility genes and utilization of hybrid vigor (heterosis). Kexue Tongbao (Chinese Science Bulletin), 67(26), Pp. 3100–3109.

Liu, X. Q., Xu, X., Tan, Y. P., Li, S. Q., Hu, J., Huang, J. Y., Yang, D. C., Li, Y. S., and Zhu, Y. G. 2004. Inheritance and molecular mapping of two fertility-restoring loci for Honglian gametophytic cytoplasmic male sterility in rice (Oryza sativa L.). Molecular Genetics and Genomics, 271(5), Pp. 586–594.

Liu, Z., Guan, C., Zhao, F., and Chen, S. 2005. Inheritance and mapping of a restorer gene for the rapeseed cytoplasmic male sterile line 681A. Plant Breeding, 124(1), Pp. 5–8.

Longin, C. F. H. 2016. Future of wheat breeding is driven by hybrid wheat and efficient strategies for pre-breeding on quantitative traits. Journal of Botanical Sciences, 3, Pp. 32–33.

Manjunathagowda, D. C., and Anjanappa, M. 2020. Identification and development of male sterile and their maintainer lines in short-day onion (Allium cepa L.) genotypes. Genetic Resources and Crop Evolution, 67, Pp. 357–365.

Mishra, S., and Kumari, V. 2018. A review on male sterility—Concepts and utilization in vegetable crops. International Journal of Current Microbiology and Applied Sciences, 7(2), Pp. 3016–3034.

Mohsin, G. M., Ahmed, F., Rahman, M. S., and Islam, M. S. 2016. Use of male sterility and synthesis of maintainer line for hybrid seed production in onion (Allium cepa L.). Bangladesh Journal of Plant Breeding and Genetics, 29(1), Pp. 31–38

Palmer, R. G., Gai, J., Dalvi, V. A., and Suso, M. J. 2011. Male sterility and hybrid production technology. In Biology and breeding of food legumes (p. 193).

Patel, T., Patel, A. I., Vashi, J., and Patel, K. 2025. Male sterility system in vegetable crops: Mechanism, breeding strategies and applications. Journal of Scientific Research and Reports, 31(8), Pp. 1015–1022.

Peng, X., Wang, K., Hu, C., Zhu, Y., Wang, T., Yang, J., Tong, J., Li, S., and Zhu, Y. 2010. The mitochondrial gene orfH79 plays a critical role in impairing both male gametophyte development and root growth in CMS-Honglian rice. BMC Plant Biology, 10, 125.

Perez-Prat, E., and Van Lookeren Campagne, M. M. 2002. Hybrid seed production and the challenge of propagating male-sterile plants. Trends in Plant Science, 7, Pp. 199–203.

Prakash, S., Ahuja, I., Upreti, H. C., Dinesh Kumar, V., Bhat, S. R., Kirti, P. B., and Chopra, V. L. 2001. Expression of male sterility in alloplasmic Brassica juncea with Erucastrum canariense cytoplasm and the development of a fertility restoration system. Plant Breeding, 120(5), Pp. 479–482.

Prasanth, K., and Kumary, I. S. 2014. Utilization of male sterility for hybrid seed production in vegetables. Current Horticulture, 2(2), Pp. 3–14

Reddy, B. V. S., Rai, K. N., Sarma, N. P., Kumar, I., and Saxena, K. B. 2004. Cytoplasmic-nuclear male sterility: Origin, evaluation and utilization. In Plant breeding: Mendelian to molecular approaches Pp. 473–499.

Ren, W., Si, J., Chen, L., Fang, Z., Zhuang, M., Lv, H., Wang, Y., Ji, J., Yu, H., and Zhang, Y. 2022. Mechanism and utilization of Ogura cytoplasmic male sterility in cruciferae crops. International Journal of Molecular Sciences, 23(16), 9099.

Rice, P., Longden, I., and Bleasby, A. 2000. EMBOSS: The European molecular biology open software suite. Trends in Genetics, 16, Pp. 276–277.

Ruge, B., Linz, A., Gaue, I., Baudis, H., Leckband, G., and Wehling, F. 2003. Molecular characterization of cytoplasmic male sterility in Lolium perenne. Vorträge für Pflanzenzüchtung, 59, Pp. 121–127.

Sanetomo, R., and Gebhardt, C. 2015. Cytoplasmic genome types of European potatoes and their effects on complex agronomic traits. BMC Plant Biology, 15, 162.

Sato, Y. 1998. The role of the Ms gene in restoring fertility in male-sterile onions (Allium cepa L.). Theoretical and Applied Genetics, 96(6–7), Pp. 994–999.

Saxena, K. B., Sharma, D., and Vales, M. I. 2018. Development and commercialization of CMS pigeon pea hybrids. Plant Breeding Reviews, 41, Pp. 103–167.

Saxena, K. B., Sultana, R., Mallikarjuna, N., Saxena, R. K., Kumar, R. V., Sawargaonkar, S. L., and Varshney, R. K. 2010. Male-sterility systems in pigeon pea and their role in enhancing yield. Plant Breeding, 129(2), Pp. 125–134.

Serba, D. D., Perumal, R., Tesso, T. T., and Min, D. 2017. Status of global pearl millet breeding programs and the way forward. Crop Science, 57(6), Pp. 2891–2905.

Sharma, P. K., Bağcı, A., and Preeti, P. 2023. Development of onion hybrids using cytoplasmic genetic male sterility. Ekin Journal of Crop Breeding and Genetics, 9(1), Pp. 64–77.

Shinjyo, C. 1969. Cytoplasmic genetic male sterility in cultivated rice, Oryza sativa L. II. The inheritance of male sterility. Japanese Journal of Genetics, 44, Pp. 149–156.

Shivanna, K. R. 2016. Male sterility and hybrid seed production in crops. Journal of Genetics and Molecular Biology, 27(1), Pp. 23–34.

Singh, D., and Khar, B. 2021. Pollen viability testing methods in horticultural crops. Journal of Plant Breeding Research, 12(2), Pp. 89–95.

Singh, H., and Khar, A. 2021. Perspectives of onion hybrid breeding in India: An overview. Indian Journal of Agricultural Sciences, 91(10), Pp. 1426–1432.

Singh, H., Sekhon, B. S., Kumar, P., Dhall, R. K., Devi, R., Dhillon, T. S., Sharma, S., Khar, A., Yadav, R. K., and Tomar, B. S. 2023. Genetic mechanisms for hybrid breeding in vegetable crops. Plants, 12(12), 2294.

Singh, M., Albertsen, M. C., and Cigan, A. M. 2021. Male fertility genes in bread wheat (Triticum aestivum L.) and their utilization for hybrid seed production. International Journal of Molecular Sciences, 22(15), 8157.

Singh, P. K., Pandey, V., Singh, M., and Sharma, S. R. 2013. Genetic improvement of cauliflower. Vegetable Science, 40(2), Pp. 121–136.

Singh, S. P., Srivastava, R., and Kumar, J. 2015. Male sterility systems in wheat and opportunities for hybrid wheat development. Acta Physiologiae Plantarum, 37, Pp. 1–13.

Sodhi, Y. S., Chandra, A., Verma, J. K., Arumugam, N., Mukhopadhyay, A., Gupta, V., Pental, D., and Pradhan, A. K. 2006. A new cytoplasmic male sterility system for hybrid seed production in Indian oilseed mustard (Brassica juncea). Theoretical and Applied Genetics, 114, Pp. 93–99

Song, X. Y., Qian, H. H., and Zhang, L. L. 2014. Cytogenetic analysis of cytoplasmic male sterility in wheat line KTP116A and molecular mapping of two thermo-sensitive restoration genes. Euphytica, 196(1), Pp. 129–136. https://doi.org/10.1007/s10681-013-1045-2

Song, X., Liu, G., and Zheng, Z. 2014. Characterization of cytoplasmic male sterility in wheat: Identification of the mitochondrial gene orf256. Plant Science, 217, Pp. 76–83.

Stamp, P., Chow Chong, S., Menzi, M., Weingartner, U., and Kaeser, O. 2000. Increase in the yield of cytoplasmic male sterile maize revisited. Crop Science, 40, Pp. 1586–1867.

Sun, Q., Hu, C., Hu, J., Li, S., and Zhu, Y. 2009. Quantitative proteomic analysis of CMS-related changes in Honglian CMS rice anther. Protein Journal, 28, Pp. 341–348.

Talukder, Z. I., Ma, G., Hulke, B. S., Jan, C. C., and Qi, L. 2019. Linkage mapping and genome-wide association studies of the Rf gene cluster in sunflower (Helianthus annuus L.) and their distribution in world sunflower collections. Frontiers in Genetics, 10, 216. https://doi.org/10.3389/fgene.2019.00216

Tang, H., Liu, H., Zhou, Y., Liu, H., Du, L., Wang, K., and Ye, X. 2021. Fertility recovery of wheat male sterility controlled by Ms2 using CRISPR/Cas9. Plant Biotechnology Journal, 19, Pp. 224–226.

Tang, H., Zheng, X., Li, C., Xie, X., Chen, Y., Chen, L., Zhao, X., Zheng, H., Zhou, J., and Ye, S. 2017. Multi-step formation, evolution, and functionalization of new cytoplasmic male sterility genes in the plant mitochondrial genomes. Cell Research, 27(1), Pp. 130–146.

Tenberge, K. B. 1999. Biology and life strategy of the ergot fungi. In Ergot Pp. 40–71. CRC Press.

Toriyama, K. 2021. Molecular basis of cytoplasmic male sterility and fertility restoration in rice. Plant Biotechnology, 38(4), Pp. 285–295.

Tyagi, V., Dhillon, S. K., Kaushik, P., and Kaur, G. 2018. Characterization for drought tolerance and physiological efficiency in novel cytoplasmic male sterile sources of sunflower (Helianthus annuus L.). Agronomy, 8(10), 232.

Wan, X., Wu, S., Li, Z., Dong, Z., An, X., Ma, B., Tian, Y., and Li, J. 2019. Maize genic male-sterility genes and their applications in hybrid breeding: Progress and perspectives. Molecular Plant, 12(3), Pp. 321–342.

Wang, Z., Zou, Y., Li, X., Zhang, Q., Chen, L., Wu, H., Su, D., Chen, Y., Guo, J., Long, Y., Zhong, Y., and Liu, Y. 2006. Cytoplasmic male sterility of rice with Boro II cytoplasm is caused by a cytotoxic peptide and is restored by two related PPR motif genes via distinct modes of mRNA silencing. The Plant Cell, 18(3), Pp. 676–687.

Wen, L., Liu, G., Li, S., Wan, C., Tao, J., Xu, K. 2007. Proteomic analysis of anthers from Honglian cytoplasmic male sterility line rice and its corresponding maintainer and hybrid. Botanical Studies, 48, Pp. 293–309.

Whitford, R., Fleury, D., Reif, J. C., Garcia, M., Okada, T., Korzun, V., and Langridge, P. 2013. Hybrid breeding in wheat: Technologies to improve hybrid wheat seed production. Journal of Experimental Botany, 64(18), Pp. 5411–5428.

Xu, H., Kong, X., Chen, F., Huang, J., Lou, X., and Zhao, J. 2015. Transcriptome analysis of Brassica napus pod using RNA-Seq and identification of lipid-related candidate genes. BMC Genomics, 16, Article 858.

Yadav, O. P., and Rai, K. N. 2013. Genetic improvement of pearl millet in India. Agricultural Research, 2(4), Pp. 275–292. https://doi.org/10.1007/s40003-013-0089-