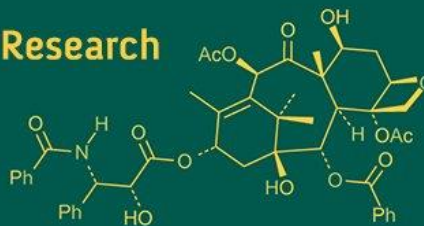


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Pollination control mechanisms in crop plants: Advances, applications and future prospects in F1 hybrid seed production

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Abstract

Hybrid breeding is one of the most effective approaches for exploiting heterosis and combining complementary traits into superior F1 cultivars. Its success depends on the reliable control of pollination so that the female parent receives pollen only from the intended male parent. Pollination control mechanisms have therefore become a central component of commercial hybrid seed production and include mechanical emasculation, chemical hybridizing agents, gynocism, self-incompatibility, genetic male sterility, cytoplasmic male sterility, cytoplasmic-genetic male sterility, environment-sensitive genetic male sterility, and transgenic systems. Each mechanism differs in genetic basis, operational requirements, environmental stability, scalability, seed purity, labour requirement and suitability for particular crops. Mechanical emasculation remains useful in crops with large flowers or low seed requirement, but its labour intensity limits large-scale application. Chemical hybridizing agents can induce temporary male sterility but are constrained by phytotoxicity, genotype dependence and environmental sensitivity. Genetic systems, particularly CMS and CGMS, have enabled large-scale hybrid seed production in numerous crops, whereas GMS and EGMS provide valuable alternatives where stable cytoplasmic systems are unavailable. Gynocism is especially important in cucurbit breeding, while self-incompatibility has contributed to hybrid production in Brassica and other crops. Modern molecular breeding has expanded the possibilities for pollination control through marker-assisted selection, genomic analysis, fertility-restorer gene discovery, transcriptomics and genome editing. In vegetable crops, the integration of classical male sterility systems with molecular markers and precision breeding is expected to improve the efficiency, stability and genetic purity of hybrid seed production. Chilli or pepper represents an important case in which hand emasculation and pollination remain widely used, while CMS, CGMS and GMS systems continue to be explored for reducing hybrid seed production costs. This review examines the biological basis, practical utilization, advantages, limitations and future prospects of major pollination control mechanisms, with particular emphasis on their application to vegetable breeding and F1 hybrid development.

Keywords: Hybrid breeding, heterosis, pollination control, male sterility, CMS, CGMS, GMS, gynocism, self-incompatibility, chemical hybridizing agents, chilli, pepper, F1 hybrid seed production, genome editing

1. Introduction

The development of high-performing F1 hybrids is a major achievement of modern plant breeding. Hybrids can express heterosis or hybrid vigour, resulting in improved yield, earliness, uniformity, stress tolerance, fruit quality and market value. In vegetables, hybrid cultivars have transformed commercial production because growers often demand uniform maturity, attractive produce, disease resistance and high yield. However, the commercial exploitation of heterosis requires a dependable system for preventing unwanted self-pollination and controlling pollen flow between parental lines.

Pollination control refers broadly to the deliberate manipulation or prevention of pollen transfer so that fertilization occurs between selected parents. In practical breeding, the objective is to produce genetically pure F1 seed by ensuring that the female parent is fertilized by the desired male parent. The uploaded doctoral seminar material identifies mechanical, chemical, genetic and transgenic mechanisms, with genetic systems including gynocism, self-incompatibility and male sterility, and conventional male sterility systems including CMS, CGMS, GMS and environment-sensitive systems.

These mechanisms provide alternative routes to overcome the biological barriers associated with controlled hybridization.

The choice of pollination control mechanism depends on floral biology, mating system, flower size, pollen production, environmental conditions, availability of restorer genes, seed multiplication economics, labour availability and regulatory requirements. In crops with large, easily accessible flowers, manual emasculation can be effective. In crops with small flowers or high-volume commercial seed production, male sterility or self-incompatibility is generally more efficient. In cucurbits, manipulation of sex expression and gynoeism can substantially reduce the need for emasculation, whereas CMS and CGMS have become important in crops such as onion and chilli. The overall trend is toward combining classical breeding with molecular diagnostics and precision breeding to achieve stable, scalable and cost-effective pollination control.

2. Importance of F1 Hybrid Breeding

The fundamental advantage of F1 hybrid breeding is the exploitation of heterosis. When genetically diverse parental lines are crossed, the resulting hybrid may outperform its parents for one or more economically important traits. Heterosis can be expressed as increased biomass, yield, vigor, earliness, stress tolerance, disease resistance or quality. In vegetable crops, commercial hybrids frequently provide a combination of uniformity and productivity that is difficult to achieve through open-pollinated varieties.

A typical hybrid breeding pipeline involves development and purification of parental lines, evaluation of combining ability, crossing of complementary parents, testing of experimental hybrids, multi-location evaluation and commercial seed multiplication. At the seed production stage, genetic purity is critical. If the female parent self-pollinates or receives pollen from an unintended source, the harvested seed will contain off-types and the commercial hybrid will lose its expected performance. Pollination control is therefore not merely a technical step but a foundation of hybrid seed quality.

Efficient pollination control also affects production economics. Manual emasculation and hand pollination can require substantial labour, whereas a stable male sterile female line can eliminate emasculation and permit efficient pollen-mediated fertilization. The presentation emphasizes that hybrid breeding requires development of parental lines, crossing complementary lines and commercial-scale F1 seed production, all of which depend on preventing unwanted pollination.

3. Principles of Pollination Control

Pollination control mechanisms can be classified according to whether they rely on physical intervention, chemical induction, naturally occurring reproductive biology, genetic male sterility or biotechnology. Mechanical systems physically remove or disable anthers. Chemical systems use compounds that disrupt pollen development or function. Genetic systems exploit traits that prevent self-fertilization or pollen production. Transgenic systems introduce engineered genes that selectively disrupt male fertility or facilitate seed production.

The ideal pollination control mechanism should provide complete or near-complete male sterility in the female

parent, stable expression under field conditions, easy identification and maintenance, minimal adverse effects on female fertility, compatibility with the desired male parent, and low production cost. It should also be scalable and capable of maintaining high genetic purity. No single system satisfies all these requirements in every crop, which explains why different approaches continue to coexist.

4. Mechanical Methods

4.1 Hand Emasculation and Controlled Pollination

Hand emasculation involves the physical removal of anthers or immature stamens from a flower before pollen shedding, followed by pollination of the receptive stigma with pollen collected from the selected male parent. It is a simple and direct method and remains important in many vegetable breeding programmes. The uploaded material lists okra, hot pepper, tomato and eggplant among crops where hand emasculation and controlled pollination are used.

The success of hand emasculation depends on the timing of flower development, the relative maturity of anthers and stigma, flower morphology and the skill of workers. Emasculation is usually performed before anther dehiscence. The emasculated flower is then protected from foreign pollen and pollinated manually when stigma receptivity is optimal. Tagging and recording of crosses are essential for maintaining pedigree identity.

The principal advantages are simplicity, flexibility and broad applicability. Breeders can cross almost any compatible parents without requiring a specific male sterility gene. The method is particularly useful during early breeding generations, for making specific crosses, and when only a small amount of hybrid seed is required. Its major disadvantages are high labour cost, slow seed production, dependence on skilled workers and the risk of accidental self-pollination or contamination. The presentation similarly identifies high production cost, possible seed-quality problems and risks of infringement or piracy as practical concerns.

5. Chemical Hybridizing Agents

Chemical hybridizing agents (CHAs), also called gametocides or chemical emasculators, are compounds that selectively inhibit male reproductive development and induce temporary or permanent male sterility. They are applied at specific developmental stages to disrupt pollen formation while ideally preserving ovule fertility. This approach can be useful when stable genetic male sterility or CMS is unavailable.

The effectiveness of a CHA depends strongly on genotype, dose, developmental stage, application method and environmental conditions. The ideal compound should induce complete male sterility without damaging the female reproductive organs, plant growth or seed set. However, achieving this selectivity is difficult. Phytotoxicity, incomplete male sterility, female sterility, environmental sensitivity and genotype specificity are major limitations. These challenges are also identified in the uploaded presentation.

CHAs have potential value in hybridization programmes because they can theoretically convert elite fertile lines into male sterile female parents without lengthy backcrossing. Nevertheless, commercial adoption has been limited by inconsistent performance and environmental effects. Future research may benefit from precision application, improved

understanding of pollen-development pathways and discovery of compounds that target male reproductive processes more selectively.

6. Gynoecism and Sex-Expression Manipulation

Gynoecism is a reproductive system in which plants produce predominantly or exclusively pistillate flowers. It is particularly valuable in cucurbit crops, where male and female flowers occur separately on the same plant or on different sex-expression types. By increasing the proportion of female flowers, breeders can simplify hybrid seed production and reduce the need for manual emasculation.

The uploaded material highlights gynoecism in bitter melon and identifies cucumber, muskmelon and squash as crops in which the trait has commercial relevance. Maintenance of gynoecious lines may require induction of staminate flowers using treatments such as gibberellic acid, silver thiosulfate or silver nitrate.

The main limitation is that gynoecious expression may not be complete or stable. Environmental conditions, genotype and plant growth regulators can influence sex expression. Isolation is essential to avoid unwanted pollen contamination, and the production of sufficient pollen from induced male flowers can become an operational challenge. Nevertheless, gynoecism remains one of the most effective biological mechanisms for hybrid seed production in cucurbits and provides an excellent example of how manipulation of reproductive biology can replace conventional emasculation.

7. Self-Incompatibility

Self-incompatibility (SI) is a genetically controlled mechanism that prevents successful fertilization between genetically related pollen and stigma. It allows plants to reject their own pollen while permitting compatible cross-pollen to fertilize the ovules. In hybrid seed production, SI can therefore reduce the need for emasculation if the female and male parents possess compatible incompatibility genotypes.

Two major forms are recognized: gametophytic self-incompatibility, in which pollen compatibility is determined by the haploid genotype of the pollen grain, and sporophytic self-incompatibility, in which pollen phenotype is determined by the diploid genotype of the pollen-producing plant. The S-locus and its multiple alleles are central to these systems. The uploaded presentation describes pollen-tube inhibition and callose deposition as components of the incompatibility response.

Self-incompatibility has practical value in Brassica vegetables and other crops. However, the system may be unstable under environmental stress, and continued selfing can weaken the incompatibility reaction in some backgrounds. High temperature and humidity may reduce the strength of SI, creating opportunities for unwanted self-pollination. These limitations necessitate careful testing of parental lines under the intended seed-production environment.

8. Male Sterility

Male sterility is the inability of a plant to produce functional pollen while retaining functional female reproductive organs. It is among the most important pollination-control mechanisms because it eliminates or reduces the need for emasculation. Male sterility may be controlled by nuclear

genes, cytoplasmic factors, interactions between cytoplasm and nuclear genes, environmental conditions or introduced transgenes.

The commercial value of male sterility arises from the possibility of growing male sterile plants as female parents and pollinating them with a selected male parent. The resulting seed is predominantly or completely hybrid, provided that the female population is sufficiently male sterile and the production field is managed correctly.

8.1 Genetic Male Sterility

Genetic male sterility (GMS) is controlled by nuclear genes, often recessive alleles. A common model involves a recessive sterile genotype, represented as *msms*, while fertile plants are *MsMs* or *Msms*. Because male sterility is inherited through the nuclear genome, maintenance generally requires fertile sister plants or heterozygous maintainer populations. The uploaded presentation identifies *ms1*, *ms3*, *ms8* and *ms10* among documented male sterility genes in chilli and emphasizes the importance of maintaining segregating populations.

A major disadvantage is segregation. In a typical recessive GMS maintenance population, fertile and sterile plants occur together, requiring identification and removal of fertile plants before flowering and pollination. The presentation highlights the 1:1 segregation burden and the labour required for accurate rouging. Escape of fertile plants can result in self-pollination and loss of hybrid seed purity. GMS is particularly useful when a CMS source is unavailable or when an elite genotype cannot be readily converted to CMS. It can also provide a useful alternative when cytoplasmic effects are undesirable. Molecular markers linked to male sterility genes can substantially improve the efficiency of GMS breeding by allowing early identification of sterile and fertile genotypes.

8.2 Cytoplasmic Male Sterility

Cytoplasmic male sterility (CMS) is a maternally inherited condition in which plants fail to produce functional pollen because of factors associated mainly with the mitochondrial genome. CMS is highly valuable in hybrid seed production because the female parent can be maintained without producing viable pollen, thereby eliminating the need for manual emasculation.

CMS systems often involve interactions between mitochondrial factors and nuclear fertility-restorer genes. Sterile cytoplasm combined with a nuclear genotype lacking effective restorer alleles results in male sterility, whereas the presence of appropriate restorer genes can restore pollen fertility in the hybrid. The uploaded presentation describes the S-cytoplasm and Rf interaction and the development of A-, B- and R-lines.

The classical three-line system consists of an A-line, which is male sterile; a B-line, which is genetically similar but fertile and serves as the maintainer; and an R-line, which carries fertility-restoring genes. A-line × B-line maintains the sterile female parent, while A-line × R-line produces the commercial F1 hybrid. This system has been widely exploited in crops including onion and other species in which the CMS system is stable and effective.

CMS conversion commonly involves repeated backcrossing of a sterile cytoplasm donor to an elite recurrent parent. Several generations of backcrossing are required to recover the nuclear genome of the recurrent parent while retaining

the sterile cytoplasm. The uploaded material illustrates backcross-based CMS conversion and highlights challenges such as cytoplasmic uniformity, stability at low temperatures, identification of Rf genes and difficulty integrating multiple traits.

A major concern is genetic vulnerability when commercial hybrids depend heavily on a single CMS source. Diverse cytoplasmic backgrounds are therefore desirable. Molecular characterization of mitochondrial genomes and reliable markers for fertility-restorer genes can reduce breeding time and improve the predictability of hybrid fertility restoration.

8.3 Cytoplasmic-Genetic Male Sterility

Cytoplasmic-genetic male sterility (CGMS) results from interaction between sterile cytoplasm and nuclear fertility-restorer genes. It is a practical extension of CMS systems and is particularly valuable where a stable A-line can be maintained and fertile hybrids can be produced through the use of suitable R-lines. In commercial seed production, the A-line provides the female parent, the B-line maintains the A-line, and the R-line restores fertility in the commercial hybrid.

CGMS is highly attractive because the female seed-production block can consist predominantly of male sterile plants, making large-scale hybrid seed production more efficient than manual emasculation. However, the success of CGMS depends on reliable fertility restoration. Restorer genes may be absent, weakly expressed or environmentally unstable in some genetic backgrounds. Molecular markers linked to Rf loci are therefore increasingly important in breeding programmes.

In chilli, CMS and CGMS have particular relevance because manual emasculation is labour intensive. The development of stable CMS sources, effective maintainers and broad-spectrum restorer lines can reduce the cost of hybrid seed production. The uploaded presentation includes chilli A-line and B-line examples and illustrates the use of CMS/CGMS in hybrid production.

8.4 Environment-Sensitive Genetic Male Sterility

Environment-sensitive genetic male sterility (EGMS) is a system in which nuclear genetic factors interact with environmental conditions to determine male fertility. The two major categories are temperature-sensitive genetic male sterility (TGMS) and photoperiod-sensitive genetic male sterility (PGMS). In a suitable environment, the plant is male sterile and can be used as a female parent; under another environment, fertility is restored and the line can be multiplied.

EGMS offers an important advantage because it can function as a two-line hybrid seed production system, reducing the need for a separate maintainer line. However, its success depends on predictable environmental thresholds. Temperature fluctuations, photoperiod variation and interactions between environmental factors can compromise sterility or fertility restoration. Therefore, precise characterization of the fertility-sensitive stage and careful selection of seed-production locations are essential.

Although EGMS has been most extensively exploited in crops such as rice, the underlying concept is relevant to broader hybrid breeding. Future research in vegetables may identify temperature- or photoperiod-responsive fertility systems that are sufficiently stable for commercial application.

9. Transgenic Male Sterility

Transgenic male sterility uses engineered genes to disrupt pollen development or to create systems that permit efficient hybrid seed production. One of the best-known approaches is the barnase-barstar system. Barnase, a ribonuclease expressed specifically in developing anthers, can induce male sterility, while barstar acts as an inhibitor of barnase and can restore fertility when appropriately expressed. The uploaded material identifies the barnase-barstar system and Seed Production Technology as transgenic approaches used in hybrid seed production.

Transgenic approaches can provide highly effective and predictable male sterility, but their adoption depends on regulatory frameworks, biosafety assessment, public acceptance and intellectual-property considerations. In many countries, regulatory requirements can make transgenic hybrid systems more complex than conventional CMS or GMS approaches. Nevertheless, these systems established important proof-of-concept principles for targeted manipulation of male fertility.

Seed Production Technology (SPT) and related systems aim to produce male sterile female parents while enabling efficient maintenance and removal of unwanted fertile plants. Such systems demonstrate how multiple genetic components can be combined to create a complete hybrid seed-production platform. The future role of these approaches will depend strongly on regulatory environments and the development of acceptable precision-breeding alternatives.

10. Molecular, Genomic and Genome-Editing Approaches

Modern molecular biology is transforming pollination control by enabling breeders to identify reproductive genes, characterize fertility-restorer loci and distinguish sterile from fertile plants at early developmental stages. Marker-assisted selection can reduce the need for extensive field screening, particularly in GMS and CGMS breeding. Markers linked to sterility genes or Rf genes can be used to select desirable plants before flowering.

Genomic approaches provide opportunities to dissect complex male fertility traits through QTL mapping, genome-wide association studies, transcriptomics, proteomics and metabolomics. Male sterility may arise from abnormalities in tapetum development, meiosis, pollen wall formation, mitochondrial function, carbohydrate metabolism or hormone regulation. Understanding these pathways can reveal new breeding targets.

Genome editing has expanded the potential for targeted manipulation of reproductive traits. CRISPR/Cas systems can be used to modify genes involved in pollen development, fertility restoration or sex expression. Unlike conventional mutagenesis, targeted editing allows breeders to modify specific genes with greater precision. In principle, edited male sterility genes could provide new two-line or three-line hybrid systems, particularly when combined with linked markers and efficient regeneration systems.

However, genome editing does not automatically solve the operational challenges of hybrid seed production. A useful system must be stable, genetically predictable, easy to maintain and economically viable. Regulatory treatment of genome-edited crops also varies among jurisdictions. Future research should therefore focus on translating molecular discoveries into robust field-level breeding systems.

11. Pollination Control in Major Vegetable Crops

Vegetable crops represent a diverse group of reproductive systems, and pollination-control strategies differ substantially among species. In tomato and eggplant, hand emasculatation is widely used for breeding crosses because flowers are accessible and crossing can be performed with reasonable precision. In commercial hybrid seed production, however, labour costs encourage the development of male sterility and other biological systems.

Cucurbits offer unique opportunities through manipulation of sex expression. Gynoeceious cucumber lines, for example, produce predominantly female flowers and can simplify hybrid seed production. Similar principles have been applied in bitter melon, muskmelon and squash. The uploaded presentation identifies these crops as commercial beneficiaries of gynoeceism.

Brassica vegetables have benefited from self-incompatibility systems and, in some cases, CMS-based hybrid production. Self-incompatibility can be highly effective when compatible parental combinations are carefully selected, although environmental conditions may influence the strength of the incompatibility reaction. The presentation identifies cabbage and cauliflower among crops where SI has commercial utility.

Onion is an important example of CMS-based hybrid seed production. The crop has a long history of exploiting cytoplasmic male sterility, and the A-line/B-line system can be used for maintenance and hybrid production. Similar CMS systems have relevance in carrot, coriander and other crops where vegetative or reproductive structures are commercially valuable.

The selection of a pollination-control system should therefore be crop specific. Floral morphology, pollination biology, genetic resources and seed-production economics all influence the best approach.

12. Special Focus on Chilli/Hot Pepper

Chilli (*Capsicum annuum* L.) is one of the most important vegetable and spice crops globally. It is cultivated for fresh green fruits, red dry fruits, paprika and processing products. Hybrid breeding in chilli targets yield, fruit quality, pungency, colour, disease resistance, heat tolerance and adaptation. However, hybrid seed production can be labour intensive because manual emasculatation and pollination are

commonly required in many breeding and commercial systems.

The reproductive biology of chilli creates opportunities and challenges for pollination control. Flowers are generally bisexual, and self-pollination can occur, although the degree of natural outcrossing varies with genotype and environmental conditions. For controlled crossing, breeders often remove anthers before dehiscence and apply pollen from the selected male parent. This approach is reliable for breeding crosses but becomes expensive when large quantities of hybrid seed are required.

Male sterility systems are therefore highly desirable in chilli. CMS and CGMS can eliminate the need for emasculatation if stable sterile lines, maintainers and restorers are available. GMS offers another route but requires removal of fertile segregants. The uploaded presentation specifically notes that chilli has documented male sterility genes and that GMS breeding requires careful identification and removal of fertile plants.

A practical chilli hybrid seed-production programme may include the following steps: identification of a stable male sterile source; conversion of elite backgrounds; development of maintainer and restorer lines; molecular characterization of fertility genes; evaluation of male sterility stability across environments; synchronization of flowering; optimization of parental row ratios; management of pollinators; rouging of off-types; and post-harvest hybrid seed quality testing.

The major research priorities for chilli include development of stable CMS/CGMS systems, identification of effective Rf genes, molecular markers for ms loci, understanding environmental effects on pollen fertility, and integration of disease resistance and fruit-quality traits into male sterile backgrounds. The presentation identifies lack of reliable markers, stability of GMS lines and identification of fertile plants as key challenges.

For modern chilli breeding programmes, the most promising strategy is likely to be an integrated system combining conventional selection with molecular markers. Marker-assisted identification of sterile and fertile plants can reduce field labour, while genomic approaches can accelerate discovery of fertility-restorer genes. Stable CMS/CGMS systems remain particularly attractive for commercial hybrids, whereas GMS can be valuable for specific breeding backgrounds that cannot be efficiently converted to CMS.

Table 1: Comparative Evaluation of Pollination Control Systems

System	Main principle	Major advantages	Major limitations	Typical applications
Hand emasculatation	Physical removal of anthers	Simple; flexible; useful for specific crosses	Labour intensive; costly at scale	Tomato, chilli, eggplant, okra
Chemical hybridizing agents	Chemical induction of male sterility	Can convert fertile lines without lengthy breeding	Phytotoxicity; genotype and environment effects	Research and selected hybridization programmes
Gynoeceism	Predominantly female flowering	Reduces emasculatation in cucurbits	Requires maintenance and controlled sex expression	Cucumber, bitter melon, muskmelon, squash
Self-incompatibility	Genetic rejection of self pollen	Natural barrier to selfing	Environmental instability; compatibility management	Cabbage, cauliflower, Brassica
GMS	Nuclear male sterility	Useful where CMS unavailable	Fertile segregants require rouging	Chilli, okra and other crops
CMS	Cytoplasm-associated pollen sterility	No emasculatation; efficient female parent	Requires stable cytoplasm and maintainer	Onion and other crops
CGMS	CMS with nuclear fertility restoration	Efficient commercial hybrid seed production	Requires effective Rf genes	Chilli and several field/vegetable crops
EGMS	Environment-dependent male sterility	Potential two-line system	Sensitive to environmental variation	Primarily cereals; potential wider use
Transgenic systems	Engineered control of male fertility	Highly targeted and effective	Regulatory and biosafety constraints	Selected commercial/research systems
Genome editing	Targeted modification of fertility genes	Precision; rapid functional validation	Regulatory and technical constraints	Emerging technology

13. Challenges and Research Gaps

Despite major progress, several challenges limit the universal adoption of pollination-control systems. First, reproductive traits can be strongly influenced by the environment. Temperature, humidity, photoperiod and plant nutritional status may affect pollen development, stigma receptivity, self-incompatibility and fertility restoration. A system that performs well in one location may fail in another.

Second, genetic background effects remain important. Introgression of male sterility or fertility-restorer genes may be accompanied by linkage drag or undesirable agronomic traits. Repeated backcrossing can recover elite backgrounds but requires several generations. Molecular markers can shorten this process, but marker validation across genetic backgrounds is essential.

Third, seed purity is a major operational challenge. In GMS systems, fertile plants must be identified and removed. In CMS/CGMS systems, off-types and pollen shedders must be eliminated. Isolation distance, pollinator management, field inspection and seed testing remain essential. The uploaded material specifically identifies contamination risks, fertile segregants and the need for skilled rouging as important limitations.

Fourth, commercial hybrid production requires synchronization of flowering between female and male parents. Even a perfectly sterile female line cannot produce adequate hybrid seed if flowering is poorly synchronized. Breeding programmes must therefore select parents with compatible flowering duration, plant architecture and environmental adaptation.

Finally, new biotechnology-based approaches face regulatory and public-acceptance considerations. The future success of genome editing and transgenic systems will depend not only on biological effectiveness but also on regulatory clarity, consumer acceptance and economic competitiveness.

14. Future Prospects

The future of pollination control is likely to be characterized by integration rather than replacement. Conventional systems such as CMS, GMS and gynocism will continue to be valuable because they are field-proven and operationally practical. At the same time, molecular breeding will improve their efficiency by identifying sterility genes, fertility-restorer genes and diagnostic markers.

The development of high-throughput genotyping and genomic prediction can accelerate the selection of parental combinations. Genome editing may allow precise creation or modification of male sterility systems, while transcriptomic and proteomic approaches can reveal reproductive pathways that were previously difficult to characterize. Combining these tools with speed breeding may shorten the time required to develop commercial hybrid parents.

For vegetable breeding, future priorities should include stable male sterility systems in chilli, tomato, eggplant and other high-value crops; improved gynocious systems in cucurbits; molecular markers for fertility restoration; and environment-resilient pollination-control mechanisms. Breeding programmes should also evaluate the total economics of each system, including seed yield per hectare, labour requirement, parental maintenance cost and genetic purity.

Climate change adds another dimension. Increasing temperatures and unpredictable weather may disrupt flowering synchrony, pollen viability and fertility restoration. Therefore, future pollination-control systems should be evaluated under diverse environments and selected for stability. Controlled-environment phenotyping combined with field validation may become increasingly important.

15. Conclusions

Pollination control is a fundamental requirement for efficient F1 hybrid development and commercial hybrid seed production. Mechanical emasculation provides flexibility and remains indispensable for many breeding crosses, but its labour intensity limits large-scale use. Chemical hybridizing agents offer an alternative route but are constrained by phytotoxicity and environmental variability. Gynocism and self-incompatibility provide powerful biological mechanisms in crops with suitable reproductive systems.

Among male sterility systems, CMS and CGMS are particularly valuable for commercial hybrid seed production because they can eliminate the need for emasculation. GMS remains useful where CMS is unavailable or unsuitable, although segregation and rouging increase production costs. EGMS provides an attractive two-line approach but depends on reliable environmental conditions. Transgenic systems demonstrate the potential of molecular manipulation, while modern genomics and genome editing are opening new possibilities for precise control of fertility.

For vegetable crops, and especially chilli, the most promising future lies in integrating conventional hybrid breeding with molecular markers, genomic analysis and precision breeding. Stable CMS/CGMS systems, robust fertility-restorer genes and reliable molecular diagnostics could significantly reduce hybrid seed production costs and improve seed purity. Overall, the development of efficient, stable and economically viable pollination-control systems will remain a major priority for next-generation hybrid breeding.

References

1. Acquah G. Principles of plant genetics and breeding. 2nd ed. Chichester: Wiley-Blackwell; 2012.
2. Allard RW. Principles of plant breeding. 2nd ed. New York: John Wiley & Sons; 1999.
3. Bohra A, Jha UC, Adhimoolam P, Bisht D, Singh NP. Cytoplasmic male sterility systems in crop plants. Plant Cell Reports. 2016.
4. Kaul MLH. Male sterility in higher plants. Berlin: Springer; 1988.
5. Kim YJ, Zhang D. Molecular control of male fertility for crop hybrid breeding. Trends in Plant Science. 2018.
6. Longin CFH, *et al.* Hybrid breeding in crops: current status and future perspectives. Theoretical and Applied Genetics. 2020.
7. Pandey S, Kumar S. Genetic mechanisms and applications of hybrid breeding in vegetable crops. Frontiers in Plant Science. 2023.
8. Singh SP, Singh AK. Chemical hybridizing agents in crop improvement. Journal of Applied Horticulture. 2004.
9. Snape JW. The utilization of male sterility in plant breeding. Euphytica. 1972.

10. Yamagishi H, Bhat SR. Cytoplasmic male sterility in Brassicaceae crops. Breeding Science. 2014.
11. Zhang D, Kang C. The molecular basis of male sterility and fertility restoration in crop plants. International Journal of Molecular Sciences. 2019.
12. Pollination control mechanisms in crop plants and their utilisation in F1 hybrid development. Seminar presentation. Saikheda: G H Rasoni University; 2026.