International Journal of Economic Plants

https://ojs.pphouse.org/index.php/IJEP

Crossref

IJEP November 2024, 11(4): 452-463

Article IJEP5725d

Review Article

Doi: HTTPS://DOI.ORG/10.23910/2/2024.5725d

# Revolutionizing Horticultural Crop Improvement: A Comprehensive Review of MAGIC Breeding

**B. C. Akhilraj[1*], J. Suresh[2], N. Nireshkumar[3], S. Raghul[4] and M. Kumar[5]**

[1]Dept. of Plantation, Spices, Medicinal and Aromatic Crops, HC & RI, TNAU, Coimbatore, Tamil Nadu (641 003), India
[2]Dept. of Horticultural, Horticultural College and Research Institute for Women, Tiruchirapalli, Tamil Nadu (620 027), India
[3]Dept. of Fruit Science, Tamil Nadu Agriculture University, Tamil Nadu (641 003), India
[4]Dept. of Agricultural Engineering, Bannari Amman Institute of Technology, Sathyamanagalam, Erode, Tamil Nadu (638 402), India
[5]ICAR-Krishi Vigyan Kendra, TNAU, Tindivanam, Tamil Nadu (604 101), India

**Corresponding Author**

B. C. Akhilraj
*e-mail*: bcakhilraj@gmail.com

**Article History**

Received on 20th August, 2024
Received in revised form on 24th October, 2024
Accepted in final form on 12th November, 2024

**Abstract**

MAGIC (Multiparent Advanced Generation Inter-Cross) breeding is a powerful approach that has gained significant attention in horticultural crop improvement. By inter crossing multiple diverse parental lines over multiple generations, MAGIC breeding aims to capture and combine genetic diversity to enhance desirable traits in the offspring. Magic breeding focuses on enhancing traits such as yield, quality, disease resistance, and stress tolerance in horticultural crops such as fruits, vegetables, ornamentals, and herbs. This method harnesses the power of genetic diversity within plant populations, utilizing advanced tools such as marker-assisted selection, genomic selection, and gene editing to accelerate the breeding process and achieve targeted outcomes. Overall, MAGIC breeding represents a promising avenue for sustainable horticultural crop improvement, offering opportunities to create cultivars that are more productive, resilient, and nutritious, thereby contributing to food security, environmental sustainability, and economic prosperity in agriculture. This review provides a comprehensive analysis of the principles, applications, and advantages of MAGIC breeding in horticultural crops. It explores the breeding process, the impact on genetic variation, trait improvement, and the potential for discovering novel gene combinations. Additionally, the review discusses the challenges, current progress, and future prospects of MAGIC breeding, shedding light on its potential to revolutionize horticultural crop improvement.

***Keywords:*** MAGIC breeding, horticulture, applications, advantages

## 1. Introduction

Magic breeding in horticultural crops is an innovative approach that integrates traditional breeding techniques with modern biotechnology and genomics to enhance the breeding process and develop improved cultivars with desirable traits (Bennurmath et al., 2022). The background of MAGIC breeding in horticultural crops lies in the need for improved crop varieties that exhibit enhanced traits such as higher yield, improved quality, disease resistance, and stress tolerance (Stadlmeieret al., 2018). Traditional breeding methods, while successful to some extent, often face limitations in capturing and utilizing the vast genetic diversity present in crop plants. This led to the development of novel breeding approaches like MAGIC, which aim to overcome these limitations and accelerate the genetic improvement of horticultural crops (Pascual et al., 2015). Historically, plant breeders have primarily relied on the use of two parental lines for crossing to develop new varieties. This approach, known as biparental breeding, has contributed to the development of several improved crop varieties (Singh and Narayanan, 2009). However, it has limitations in terms of genetic diversity and the ability to capture complex traits influenced by multiple genes (Gurung et al., 2022). In the late 20th century, there was a growing recognition of the importance of genetic diversity and the need to harness it for crop improvement. This led to the emergence of methods such as multiparental crosses and nested association mapping (NAM). These approaches involved crossing multiple parental lines to create diverse populations and exploiting the recombination and segregation of genetic material in subsequent generations (Teja et al., 2023; Giridhar et al., 2016).

MAGIC breeding, specifically developed by Cavanagh et al. (2008), builds upon these earlier approaches and has gained popularity in horticultural crop breeding. MAGIC populations are derived from crossing multiple parental lines, typically between 8 to 32 lines or more, and subsequent generations involve intercrossing and recombination among the offspring (Ravi et al., 2022). This process allows for the accumulation and reshuffling of genetic variation, leading to the creation of highly diverse populations (Huang et al., 2015). The term "MAGIC" was coined to emphasize the advanced generation of the population and the incorporation of diverse parental lines. The method has been successfully applied in various crop species, including horticultural crops like tomato, maize, brassicas, and fruit crops (Barchi et al., 2019, Pascual et al., 2015). MAGIC breeding in horticultural crops has shown promise in improving various traits of interest, such as yield, quality, disease resistance, and stress tolerance Kover et al., 2009; Bandillo et al., 2013. It offers an opportunity to access and combine the favorable alleles from diverse parental lines, thereby increasing the genetic variation available for selection. This approach allows breeders to explore a broader genetic space and discover novel gene combinations that can lead to superior crop varieties (Sahu et al., 2018). With advancements in genomics and high-throughput phenotyping, MAGIC breeding has been further empowered to identify the underlying genetic basis of complex traits and facilitate the selection of desirable genotypes in an efficient manner. This has opened new avenues for crop improvement and has the potential to revolutionize the breeding strategies employed in horticultural crops (Saidaiah et al., 2021). Overall, the background of MAGIC breeding in horticultural crops stems from the recognition of the need for increased genetic diversity and the limitations of traditional breeding methods (Sharma et al., 2016). By utilizing multiple parental lines and promoting genetic recombination, MAGIC breeding offers a promising approach to enhance the genetic variation and improve desirable traits in horticultural crops (Saisupriya et al., 2022; Bandillo et al., 2013).

## 2. Principles of MAGIC Breeding

MAGIC breeding utilizes a diverse set of parental lines, typically multiple elite cultivars or germplasm sources, to create a genetically diverse population (Bandillo et al., 2013). These parents are crossed in various combinations over multiple generations, leading to increased genetic recombination and the generation of a larger number of genetic variations in the offspring.

### *2.1. Genetic diversity*

The aim of MAGIC breeding is to maximize the genetic diversity within a population. By incorporating multiple parental lines, each carrying different desirable traits, the resulting population becomes more diverse. This genetic diversity enables the selection of superior individuals with a wide range of desirable traits (Bandillo et al., 2013 and Huynh et al., 2018). In this approach, genetic diversity refers to the wide array of genetic variations present among the parental lines used in breeding programs. This diversity encompasses allelic variations, gene combinations, and genomic compositions among different parental sources. Leveraging this diversity is crucial as it allows breeders to explore a vast genetic landscape, capturing unique and favorable traits distributed across various parental lines (Arrones et al., 2020).

Horticultural crops inherently possess diverse traits, including flavor, color, shape, nutritional content, and adaptability to different environments (Kushanov et al., 2021). By integrating genetically diverse parental lines, breeders can create populations with extensive genetic recombination, facilitating the generation of novel gene combinations in each subsequent generation (Bandillo et al., 2013). This genetic reshuffling not only fosters the development of new cultivars with improved traits but also ensures a reservoir of genetic variability, enhancing adaptability, resilience to environmental stresses, and the potential for continued crop improvement in response to evolving challenges in agriculture (Li et al., 2014). Genetic diversity, thus, forms the bedrock of innovation and progress in breeding programs aimed at enhancing horticultural crops for quality, productivity, and resilience (Bandillo et al., 2013).

### *2.2. Recombination*

Through successive generations of intercrossing, the genetic material from different parental lines gets reshuffled, resulting in increased recombination. This recombination creates new combinations of genetic variants, allowing for the expression of novel phenotypes and the accumulation of favourable alleles (Huynh et al., 2018). This mechanism involves the reshuffling and recombination of genetic material during the mating of diverse parental lines. In horticultural crops, recombination occurs when genes from different parental sources combine, creating novel gene combinations in the offspring (Dinesh et al., 2023).

This genetic reshuffling, facilitated through multiple rounds of controlled crosses and generations, enables the creation of vast genetic diversity within breeding populations. The exchange of genetic material during recombination not only generates novel combinations of favorable traits but also breaks linkages between genes, allowing for independent assortment and the creation of unique genetic profiles in subsequent generations (Dell'Acqua et al., 2015). This process is crucial as it mimics the natural genetic mixing observed in populations, leading to the production of diverse offspring with an array of phenotypic variations. Recombination serves as a catalyst for innovation in breeding programs, empowering breeders to select for and amplify desirable traits while simultaneously expanding the genetic base and adaptability of horticultural crops to meet evolving agricultural and market demands (Stadlmeier et al., 2018).

### *2.3. Phenotypic evaluation*

MAGIC populations are extensively phenotyped to assess various traits of interest. This evaluation involves measuring and recording traits such as yield, quality, disease resistance, and other agronomically important characteristics. By evaluating a large number of individuals within the MAGIC population, breeders can identify superior individuals with the desired traits (Huynh et al., 2018). This evaluation process involves the systematic and comprehensive assessment of observable traits or characteristics displayed by the progeny resulting from diverse parental crosses. In horticultural crops, these traits might encompass a wide spectrum, including but not limited to fruit quality, size, shape, color, taste, nutritional content, disease resistance, and adaptability to varying environmental conditions (Arrones et al., 2020).

The evaluation is often carried out through rigorous field trials, controlled environments, or specialized testing methods tailored to specific traits of interest. Breeders meticulously analyze and quantify these traits to identify individuals exhibiting superior characteristics aligned with breeding objectives (Samantara et al., 2021). This meticulous phenotypic assessment allows for the precise selection of plants with the most desirable traits, ensuring the advancement of individuals carrying the genetic makeup contributing to improved cultivars (Ibrahim et al., 2010). Moreover, phenotypic evaluation acts as a critical feedback loop, providing valuable data to inform subsequent breeding cycles, refining breeding strategies, and guiding the selection of parental lines for further crossings, thereby perpetuating the iterative process of genetic improvement in horticultural crops (Singh et al., 2015).

### *2.4. Selection and trait improvement*

Based on the phenotypic evaluation, individuals showing superior performance for target traits are selected. These selected individuals are used as parents for the next breeding cycle, allowing for the accumulation and concentration of desirable traits in subsequent generations. This iterative process of selection and breeding leads to the development of improved horticultural varieties. This phase involves the meticulous scrutiny of offspring resulting from multiparental crosses to pinpoint individuals exhibiting superior characteristics aligned with breeding objectives. Horticultural crops present a diverse array of traits-such as taste, aroma, color, shape, yield, disease resistance, and nutritional content-that are assessed through rigorous phenotypic evaluations (Singh et al., 2015).

The selection process aims to identify and advance individuals harboring a combination of traits valued by consumers, producers, and the market. Through iterative cycles of selection, breeders not only consolidate and concentrate desirable alleles for target traits but also eliminate undesirable traits (Cockram and Mackay, 2018). This selection process, often aided by advanced genomic tools and marker-assisted selection, accelerates the development of cultivars with enhanced performance, adaptability, and market appeal (Grattapaglia, 2022). Additionally, the continual refinement of breeding populations through selection ensures the progressive improvement and fine-tuning of horticultural crops, meeting evolving consumer demands, production challenges, and environmental constraints (Vishwakarma et al., 2022).

### *2.5. Participatory approach*

MAGIC breeding often involves collaboration between breeders, farmers, and other stakeholders. This participatory approach allows for the inclusion of various perspectives and ensures that the developed varieties meet the needs and preferences of the end-users (Colley et al., 2021). By employing these principles, MAGIC breeding offers a powerful approach to enhance the genetic diversity and accelerate the development of improved horticultural crop varieties with superior traits and adaptability. This approach involves engaging various stakeholders, including farmers, consumers, chefs, marketers, and other end-users, throughout the breeding cycle (Narayanasamy, 2009).

Farmers' experiences and preferences, for instance, are valuable in identifying traits that enhance productivity, disease resistance, and suitability for specific agroecological conditions. Similarly, chefs and consumers contribute by emphasizing taste, texture, appearance, and culinary attributes that appeal to end-users (Neef and Neubert, 2011). Incorporating these diverse perspectives into breeding objectives ensures the development of cultivars that align with market demands and consumer preferences. Moreover, this inclusive approach fosters transparency, builds trust, and creates a sense of ownership among stakeholders, enhancing the adoption and acceptance of new cultivars in the market (Mukankusi et al., 2019). By integrating the voices of those who ultimately utilize and benefit from horticultural crops, the participatory approach ensures the development of cultivars that not only meet agronomic standards but also satisfy consumer needs and preferences, ultimately enhancing the success and impact of MAGIC breeding programs (Hickey and Mohan, 2005).

## 3. Application of MAGIC Breeding in Horticultural Crops

MAGIC (Multiparent Advanced Generation Inter-Crossing) breeding has various applications in horticultural crops, offering several benefits for crop improvement (Barchi et al., 2019, Pascual et al., 2015). Here are some key applications of MAGIC breeding in horticulture:

### *3.1. Genetic gain and trait improvement*

MAGIC breeding allows for the rapid accumulation and combination of favorable genetic variations from multiple parental lines. This approach facilitates the simultaneous improvement of multiple traits, including yield, quality, disease resistance, tolerance to abiotic stresses, and nutritional characteristics (Pascual et al., 2015). By exploiting the genetic diversity present in the MAGIC population, breeders can select individuals with superior trait performances, leading to significant genetic gains in horticultural crops (Varshney et al., 2009). Through the systematic integration of diverse parental lines and recurrent cycles of recombination, selection, and evaluation, MAGIC breeding aims to drive genetic gain-signifying the progressive enhancement in the overall genetic makeup of plant populations (Huang et al., 2015). This process involves the cumulative increase in frequencies of favorable alleles associated with desired traits, leading to improved cultivars over successive breeding cycles.

Horticultural crops encompass a spectrum of traits, from taste, texture, and aroma to disease resistance, yield, and nutritional content, each subject to enhancement through MAGIC breeding (Xu et al., 2017). The iterative nature of the breeding approach allows for the accumulation and concentration of beneficial alleles, resulting in cultivars exhibiting heightened productivity, adaptability to varying environments, and qualities that align with consumer preferences (Huynh et al., 2018). Genetic gain, thus, signifies the continuous improvement and refinement of horticultural crops, reflecting the cumulative impact of MAGIC breeding in delivering cultivars that meet evolving market demands, ensure agricultural sustainability, and contribute to global food security (Pascual et al., 2015).

*3.2. Adaptation to diverse environments*

Horticultural crops often face diverse environmental conditions, such as variations in temperature, humidity, soil types, and biotic stresses. MAGIC breeding enables the creation of genetically diverse populations, which increases the likelihood of capturing alleles that confer adaptability to specific environments (Arrones et al., 2020). By subjecting these populations to different growing conditions and selecting for desirable traits, breeders can develop cultivars that are well-suited for specific ecological niches or geographic regions. This approach capitalizes on the genetic diversity inherent in multiparental crosses, enabling the creation of populations with broad genetic backgrounds (Bandillo et al., 2013). Horticultural crops face a spectrum of environmental challenges, including varying climatic conditions, soil types, pest pressures, and disease prevalence. Through the integration of diverse parental lines, MAGIC breeding facilitates the development of cultivars with enhanced adaptability and resilience (Chapman, 2008).

This adaptation spans traits such as drought tolerance, heat or cold resistance, pest and disease resistance, and suitability for specific soil types. By harnessing the natural variation present in the breeding populations, breeders select and advance individuals that exhibit superior performance across multiple environments (Scott et al., 2020). This process not only ensures the creation of cultivars that are better equipped to withstand diverse stressors but also contributes to sustainable agriculture by reducing dependency on agrochemicals and improving resource-use efficiency (Prohens et al., 2017). Ultimately, the adaptation of horticultural crops to diverse environments through MAGIC breeding represents a crucial avenue for ensuring food security, increasing agricultural productivity, and fostering resilience in the face of changing climatic conditions and agricultural challenges (Gaur et al., 2019).

*3.3. Broadening the genetic base*

Traditional breeding methods often rely on a limited number of parental lines, which can lead to a narrow genetic base in crop populations (Samantara et al., 2021). MAGIC breeding addresses this limitation by incorporating numerous diverse parents, broadening the genetic base of the resulting population (Roy and Shil, 2022). This increased genetic diversity enhances the potential for novel allele combinations, leading to the development of improved varieties with expanded genetic adaptability and resilience (Singh et al., 2022). Horticultural crops often have limited genetic variability due to historical breeding practices or domestication bottlenecks (Huang et al., 2015). MAGIC breeding circumvents these constraints by amalgamating diverse parental lines, encompassing various gene pools, wild relatives, landraces, and modern cultivars. By incorporating a broad array of genetic backgrounds, this approach serves to break through genetic constraints and enrich the genetic base of breeding populations (Cavanagh et al., 2008).

The amalgamation of diverse genetic sources enhances the potential for novel genetic combinations, bringing forth traits not found within the narrow confines of traditional breeding pools. This strategy not only mitigates the risks associated with genetic uniformity but also bolsters the resilience of cultivated varieties against biotic and abiotic stresses (Zaw et al., 2019). Broadening the genetic base through MAGIC breeding cultivates a reservoir of genetic variability, fueling continuous innovation and enabling breeders to develop cultivars with improved adaptation, productivity, and quality traits, thus fortifying the sustainability and longevity of horticultural crop improvement programs (Agostino and Tripodi, 2017).

*3.4. Disease resistance and pest tolerance*

Horticultural crops are susceptible to a wide range of diseases and pests. MAGIC breeding enables the identification and introgression of genes or alleles conferring resistance or tolerance to specific pathogens or pests (Scott et al., 2020). By intercrossing multiple parents with diverse resistance profiles, breeders can generate populations with enhanced disease resistance or pest tolerance, providing sustainable solutions for crop protection. These threats pose substantial challenges to horticultural crop productivity and quality. MAGIC breeding harnesses the genetic diversity from multiple parental lines to bolster the innate defenses of cultivated varieties (Samantara et al., 2021).

Through repeated cycles of recombination and selection, breeders identify and consolidate genetic factors associated with resistance to a diverse array of diseases and pests. This approach not only broadens the spectrum of resistance traits but also reduces the likelihood of disease and pest-related losses. By integrating diverse genetic backgrounds, breeders bolster the genetic resilience of cultivars, mitigating the risks of pathogen and pest outbreaks that could otherwise devastate entire crops (Jimenez-Galindo et al., 2019). The resulting cultivars exhibit enhanced resistance or tolerance, reducing the reliance on chemical interventions while fostering sustainable and environmentally friendly crop production practices (Scott et al., 2020). The application of MAGIC breeding in conferring disease resistance and pest tolerance in horticultural crops thus stands as a critical strategy in ensuring crop health, stability, and the long-term sustainability of agricultural systems (Janila et al., 2016).

*3.5. Complex trait analysis*

Some traits in horticultural crops are controlled by multiple genes and exhibit complex inheritance patterns. MAGIC breeding offers a powerful tool for dissecting and understanding the genetic architecture of complex traits. By analyzing the segregation patterns and phenotypic data from the diverse MAGIC population, breeders can gain insights into the genetic interactions underlying these complex traits, enabling more effective breeding strategies (Huang et al., 2015 and Wankhade et al., 2021). Horticultural crops often exhibit complex traits-such as fruit quality, yield, nutritional content, and stress tolerance-that are governed by numerous interacting genes and environmental factors (Phan and Sim, 2017).

MAGIC breeding, with its diverse parental lines and multiple recombination cycles, facilitates the dissection and understanding of these intricate trait architectures (Huang et al., 2015). By analyzing large, diverse populations resulting from multiparental crosses, breeders gain insights into the genetic basis of these complex traits (Bandillo et al., 2018). Through sophisticated phenotyping, genomic analyses, and statistical tools, breeders unravel the genetic networks contributing to trait variations, facilitating the identification of key genomic regions associated with desired traits (Cavanagh et al., 2008). This approach not only enables the dissection of complex traits but also allows for the selection and manipulation of multiple genes underlying these traits (Can et al., 2019). Thus, complex trait analysis within MAGIC breeding programs in horticultural crops represents a powerful strategy for unraveling the genetic complexities of valuable traits, accelerating trait improvement, and enhancing the precision and efficiency of breeding efforts to develop cultivars with tailored characteristics meeting diverse consumer and market demands (Huynh et al., 2018).

*3.6. Participatory breeding and farmer preferences*

MAGIC breeding can be applied in participatory breeding programs, involving collaboration with farmers and stakeholders. This approach ensures that the developed varieties align with farmer preferences, local market demands, and consumer preferences (Campanelli et al., 2019). By incorporating diverse stakeholders in the breeding process, MAGIC breeding helps to create varieties that are more readily adopted by farmers and have a higher likelihood of success in the marketplace (Hufford et al., 2019). Through engaging farmers in breeding programs, breeders gain valuable insights into the traits and characteristics that are vital for successful crop cultivation, resilience, and market acceptance (Colley et al., 2021).

Participatory breeding involves collaborative efforts, where farmers actively participate in selecting and evaluating cultivars based on their agronomic performance, adaptability to local environments, pest and disease resistance, and post-harvest qualities (Ebert, 2020). Understanding farmer preferences not only ensures that cultivars meet the practical needs of agricultural production but also enhances their adoption and utilization by farming communities (Samantara et al., 2021). By incorporating farmer feedback and preferences into breeding objectives, MAGIC breeding programs produce cultivars aligned with local needs, increasing their likelihood of successful adoption, and positively impacting the livelihoods of farmers (Sogbohossou et al., 2018). This participatory approach fosters a sense of ownership among farmers, promotes the exchange of valuable knowledge, and strengthens the resilience and sustainability of horticultural crop production systems (Hoagland et al., 2015).

## 4. Advantages of MAGIC Breeding

MAGIC (Multiparent Advanced Generation Inter-Crossing) breeding offers several advantages for improving horticultural crops. Here are some key advantages of using MAGIC breeding in horticulture:

*4.1. Increased genetic diversity*

MAGIC breeding involves the use of multiple diverse parental lines, resulting in a larger genetic pool for crop improvement. This increased genetic diversity allows for a wider range of potential combinations of alleles and genetic variations. The greater genetic diversity enhances the chances of capturing desirable traits and genetic adaptations, leading to improved crop performance (Samineni et al., 2021 and Johal et al., 2008).

*4.2. Enhanced trait variation*

By intercrossing multiple parental lines, MAGIC breeding promotes recombination and the creation of novel genetic combinations. This process generates a high level of trait variation within the population, including both known and unknown genetic variants (Singh and Shrivastav, 2023). The extensive trait variation provides breeders with a broader selection of individuals exhibiting desirable traits, facilitating the identification of superior genotypes for further breeding (Johal et al ., 2008).

*4.3. Accelerated genetic gain*

The utilization of multiple parents in MAGIC breeding enables the simultaneous selection and accumulation of desirable alleles for multiple traits (Xu et al., 2017). This approach accelerates the genetic gain in horticultural crops by integrating favorable genetic variations from different sources. Compared to traditional breeding methods, MAGIC breeding can expedite the development of improved varieties with superior traits, potentially reducing the breeding cycle length (Sinha et al., 2023).

*4.4. Complex trait dissection*

Many traits in horticultural crops are governed by the interaction of multiple genes and environmental factors. MAGIC breeding provides a valuable tool for dissecting complex traits and understanding their genetic architecture. By analyzing the phenotypic and genotypic data from the diverse MAGIC population, breeders can unravel the genetic interactions and identify specific genomic regions associated with complex traits, facilitating more targeted breeding efforts (Lopez-Malvar et al., 2021).

*4.5. Adaptation to changing environments*

Horticultural crops face challenges from changing environmental conditions, such as climate variability and emerging pests and diseases. The use of multiple parents in MAGIC breeding increases the chances of incorporating genetic adaptations to diverse environmental stresses. This enhances the resilience and adaptability of horticultural varieties, ensuring their performance and productivity under varying growing conditions (Renzi et al., 2022).

*4.6. Combining favorable traits*

MAGIC breeding allows for the combination of multiple desirable traits within a single population. The diverse parental lines possess different sets of favorable alleles for various traits, enabling the selection of individuals with a combination of desired characteristics. This trait stacking capability facilitates the development of cultivars with improved agronomic performance, quality attributes, disease resistance, and other desirable traits (Butron et al., 2019).

*4.7. Farmer participation and market relevance*

MAGIC breeding can involve participatory approaches, engaging farmers and stakeholders in the breeding process. This ensures that the developed varieties align with farmer preferences, market demands, and consumer preferences. By incorporating diverse perspectives, MAGIC breeding helps create cultivars that are better suited to local conditions, have higher market acceptance, and meet specific end-user requirements. Overall, the advantages of MAGIC breeding in horticultural crops include increased genetic diversity, enhanced trait variation, accelerated genetic gain, complex trait dissection, adaptation to changing environments, the combination of favorable traits, and farmer participation. These advantages contribute to the development of improved varieties with enhanced performance, adaptability, and market suitability in horticultural crop production (Nkomo et al., 2021).

## 5. Challenges and Limitations

While MAGIC (Multiparent Advanced Generation Inter-Crossing) breeding offers numerous advantages, it also faces several challenges and limitations when applied to horticultural crops. Here are some key challenges and limitations associated with MAGIC breeding:

*5.1. Resource intensiveness*

MAGIC breeding requires substantial resources in terms of time, labor, and infrastructure. The development and maintenance of diverse parental lines, conducting multiple crosses, managing large populations, and phenotypic evaluations can be resource-intensive (Ongom and Ejeta, 2018). This can limit the widespread adoption of MAGIC breeding, particularly in settings with limited breeding resources and infrastructure.The implementation of multiparental crosses, the generation of diverse populations, and the recurrent cycles of recombination, selection, and evaluation demand considerable resources. The need for extensive phenotypic and genotypic analyses to discern complex traits adds to the resource burden. Additionally, the utilization of advanced technologies for genotyping and data analysis further amplifies the cost and expertise required (Cavanagh et al., 2008). Moreover, the extensive field trials and controlled environments essential for accurate phenotypic evaluations contribute to the resource intensiveness. This intensive resource demand poses challenges for smaller breeding programs or those with limited access to funding and advanced technologies, potentially limiting their ability to fully engage in MAGIC breeding endeavors (Arrones et al., 2020). Addressing these resource constraints while maintaining the rigor and efficiency of breeding programs remains a critical challenge in realizing the full potential of MAGIC breeding in enhancing horticultural crops. Efforts to streamline methodologies, foster collaborations, and optimize resource utilization are imperative to overcome these limitations and broaden the accessibility of MAGIC breeding across diverse agricultural contexts (Li et al., 2014).

*5.2. Complexity of analysis*

The analysis and interpretation of data generated from MAGIC populations can be complex. The increased genetic diversity and recombination events make the genetic analysis more challenging, requiring sophisticated statistical methods and computational tools. The dissection of complex traits and identification of specific genomic regions associated with desirable traits can be time-consuming and technically demanding (Verbyla et al., 2014). The sheer magnitude of genetic diversity resulting from multiparental crosses, combined with the multifaceted nature of traits influenced by multiple genes and environmental factors, poses significant analytical challenges. Comprehensive phenotypic evaluations and sophisticated genomic analyses are required to decipher the genetic architecture underlying complex traits (Hickey and Mohan, 2005). The need to disentangle numerous genetic interactions and identify specific genomic regions associated with target traits demands sophisticated statistical methodologies and bioinformatics tools. Moreover, integrating and interpreting vast datasets generated from genotyping, phenotyping, and multi-environment trials necessitates expertise in data analysis and computational resources (Neef and Neubert, 2011). This complexity in analysis not only increases the demand for specialized skills and resources but also introduces challenges in data management, quality control, and result interpretation. Addressing the complexities of data analysis remains a critical hurdle in harnessing the full potential of MAGIC breeding, emphasizing the need for continuous advancements in analytical methods, data integration techniques, and training to effectively handle the intricacies inherent in breeding programs for horticultural crops (Colley et al., 2021).

*5.3. Population size and management*

Large population sizes are often required in MAGIC breeding to capture sufficient genetic diversity and increase the chances of obtaining desirable trait combinations (Huynh et al., 2018). Managing and evaluating such large populations can be logistically demanding, requiring careful design, field management, and data collection. This challenge is particularly pronounced when dealing with perennial horticultural crops that have longer breeding cycles.The necessity for adequate population sizes in multiparental crosses to capture and retain genetic diversity poses logistical challenges in population management (Kushanov et al., 2021). Balancing the size of the breeding population is crucial-too small a population may limit genetic diversity, while excessively large populations can escalate resource demands and complicate the breeding process. Moreover, managing and maintaining these diverse populations throughout numerous breeding cycles requires meticulous planning, substantial infrastructure, and labor-intensive efforts (Bandillo et al., 2013). Ensuring proper handling, phenotypic evaluations, genotypic data collection, and maintaining the integrity of genetic diversity throughout generations demands significant resources and expertise. Additionally, maintaining accurate pedigree records and preventing genetic drift or unintended selection pressures are critical but challenging aspects of population management (Dinesh et al., 2023). Efficient population management strategies and protocols are essential to mitigate these challenges, ensuring the maintenance of genetic diversity, minimizing resource intensiveness, and optimizing the effectiveness of MAGIC breeding programs in developing improved horticultural cultivars (Dell'Acqua et al., 2015).

*5.4. Genetic linkage drag*

MAGIC breeding involves multiple cycles of recombination, which can lead to the unintentional co-inheritance of undesirable traits or genetic linkages. This phenomenon, known as genetic linkage drag, can hinder the selection and fixation of specific desirable traits. It may require additional backcrossing or fine-tuning of breeding strategies to separate desirable traits from undesirable ones, thereby increasing the breeding timeline (Cavanagh et al., 2008). This linkage occurs due to the physical proximity of genes on a chromosome, causing them to be inherited together more often than expected by chance. In horticultural crops, where numerous complex traits are governed by multiple genes, the potential for genetic linkage drag is heightened (Narayanasamy, 2009). As breeders aim to select for specific traits, they might unintentionally carry along linked genetic material that diminishes the expression of desirable traits or introduces undesirable characteristics. This phenomenon hampers the breeder's ability to independently select for and manipulate individual traits of interest, leading to challenges in breaking unwanted linkages and separating the desired traits from unfavorable genetic factors (Mukankusi et al., 2019). Addressing genetic linkage drag necessitates sophisticated breeding strategies, including larger population sizes, more extensive recombination, and precise molecular marker-assisted selection to dissociate linked traits and enable the targeted improvement of horticultural crops. Efforts to minimize genetic linkage drag remain pivotal to ensure the successful development of improved cultivars through MAGIC breeding without unintended associations hindering the expression of desirable traits (Vishwakarma et al., 2022).

*5.5. Breeding cycle length*

While MAGIC breeding can potentially accelerate the genetic gain, the overall breeding cycle length can still be considerable. It involves multiple generations of intercrossing and selection to accumulate and concentrate desirable traits (Camargo et al., 2016). The need for successive generations to achieve significant improvements can delay the release of improved cultivars, especially for perennial horticultural crops with long breeding cycles.The complexity inherent in multiparental crosses, coupled with the need for repeated cycles of recombination, phenotypic evaluation, and selection, significantly extends the breeding timeline (Stadlmeier et al., 2018). Horticultural crops often have longer breeding cycles compared to certain staple crops due to their diverse and complex traits, necessitating prolonged evaluations across multiple growing seasons. The protracted breeding cycle length poses challenges in terms of resource allocation, breeding program management, and responding to dynamic market demands (Samantara et al., 2021). Delays in releasing improved cultivars to farmers can hinder the timely adoption of resilient and productive varieties. Shortening the breeding cycle while maintaining the efficacy of selection and genetic improvement remains a substantial challenge, requiring innovations in breeding methodologies, efficient use of genomic tools, and optimization of field trial protocols. Streamlining the breeding process without compromising the precision and effectiveness of MAGIC breeding is crucial for ensuring its practical applicability and broader impact in enhancing horticultural crops (Arrones et al., 2020).

*5.6. Limited parental diversity*

The success of MAGIC breeding depends on the availability and genetic diversity of suitable parental lines. In some horticultural crops, the number of genetically diverse and well-characterized parental lines may be limited. This constraint can restrict the breadth of genetic variation that can be incorporated into the MAGIC populations, potentially affecting the extent of genetic gain achievable (Singh et al., 2015). Horticultural crops may exhibit restricted genetic diversity due to historical breeding practices, domestication bottlenecks, or limited access to diverse germplasm resources. Inadequate parental diversity can curtail the breadth and depth of genetic variation within breeding populations, hindering the creation of novel gene combinations and potentially limiting the spectrum of traits accessible for improvement (Grattapaglia, 2022). A narrow genetic base might result in fewer options for selecting favorable alleles, constraining the breeding program's ability to capture and harness the full spectrum of desirable traits. Overcoming this limitation requires concerted efforts to expand the available parental diversity by sourcing and incorporating a broader range of germplasm and wild relatives into breeding programs (Cockram and Mackay, 2018). Strategies aimed at leveraging untapped genetic resources and innovative approaches to introduce novel genetic variation are essential to mitigate the challenges posed by limited parental diversity, enabling more effective and impactful MAGIC breeding efforts in horticultural crops (Ibrahim et al., 2010).

### *5.7. Complex inheritance and polygenic traits*

Certain traits in horticultural crops exhibit complex inheritance patterns and are controlled by multiple genes or quantitative trait loci (QTLs). Dissecting and manipulating these polygenic traits through MAGIC breeding can be challenging. The identification and characterization of specific QTLs associated with complex traits require advanced molecular techniques, extensive phenotypic data, and precise genotyping methods (Connor et al., 2019). Despite these challenges and limitations, MAGIC breeding continues to be a promising approach for crop improvement in horticultural crops. Addressing these challenges through advancements in breeding technologies, collaborative efforts, and improved resources can further enhance the effectiveness and adoption of MAGIC breeding in horticulture (Arrones et al., 2020).

## 6. Current Progress and Success Stories

As of my knowledge cutoff in September 2021, there were limited specific success stories of MAGIC breeding in horticultural crops available. However, the adoption of MAGIC breeding has shown promise and progress in various horticultural crops. Here are some examples of the current progress and potential success stories of MAGIC breeding in horticulture:

### *6.1. Tomato*

MAGIC populations have been developed in tomato to enhance the genetic diversity and accelerate the breeding process (Pascual et al., 2015). These populations have been used to study and improve various traits such as fruit quality, disease resistance, and yield components. MAGIC breeding has shown potential in combining multiple desirable traits, including improved flavor, extended shelf life, and resistance to diseases such as tomato yellow leaf curl virus (Campanelli et al., 2019).

### *6.2. Maize*

MAGIC breeding has gained traction in maize, a crop that has been extensively studied for its genetic architecture and trait variation (Jiménez-Galindo et al., 2019). Researchers have used MAGIC populations in maize to dissect the genetic basis of complex traits like yield, drought tolerance, and disease resistance. The application of MAGIC breeding in maize has facilitated the identification of key genomic regions and candidate genes associated with these traits (Septiani et al., 2019).

### *6.3. Apple*

MAGIC breeding has been initiated in apple to address challenges related to disease resistance, fruit quality, and production efficiency. By intercrossing diverse parental lines, MAGIC populations have been created to study and improve traits such as scab resistance, fruit flavor, texture, and storage characteristics. These efforts aim to develop apple cultivars with enhanced disease resistance and consumer appeal (Bus et al ., 2019).

### *6.4. Brassica vegetables*

MAGIC breeding has been employed in brassica crops like broccoli and cabbage to enhance traits such as yield, nutritional quality, and pest resistance (Yan et al ., 2020). By combining diverse parental lines, MAGIC populations have been used to uncover the genetic basis of complex traits and develop improved varieties. These efforts have the potential to contribute to the development of nutrient-rich and high-yielding brassica vegetable cultivars.

## 7. Future Prospects and Directions

MAGIC (Multiparent Advanced Generation Inter-Crossing) breeding holds great potential for the future advancement of horticultural crops. Here are some key future prospects and directions for MAGIC breeding in horticulture:

1. Expanding Genetic Diversity: Further efforts can be made to increase the genetic diversity of parental lines used in MAGIC breeding. This can involve the inclusion of additional wild relatives, landraces, or exotic germplasm to broaden the genetic base of horticultural crops. By incorporating diverse genetic resources, breeders can access new alleles and traits that can contribute to improved crop performance and adaptation to changing environments.

2. Trait Stacking and Multi-Trait Selection: MAGIC breeding provides opportunities for trait stacking, which involves combining multiple desirable traits within a single population.

Future directions of MAGIC breeding can focus on the simultaneous improvement of multiple agronomic traits, including yield, quality, disease resistance, abiotic stress tolerance, and nutritional characteristics. Multi-trait selection approaches can be developed to efficiently select individuals with optimal combinations of desirable traits.

3. High-Throughput Phenotyping and Genotyping: Advancements in high-throughput phenotyping and genotyping technologies can greatly accelerate the progress of MAGIC breeding. Automated phenotyping platforms, remote sensing, and imaging techniques can enable the efficient collection of large-scale phenotypic data for diverse traits. Similarly, advances in genotyping technologies, such as genotyping-by-sequencing (GBS) and next-generation sequencing, can facilitate the genotypic characterization of MAGIC populations, enabling more precise trait mapping and selection.

4. Genomic Selection and Prediction: The integration of genomic selection and prediction methods with MAGIC breeding can expedite the breeding process. By combining genomic information from the MAGIC population with phenotypic data, genomic prediction models can be developed to estimate the breeding values of individuals and select for desired traits. This approach can help prioritize individuals with the highest genetic potential, increasing the efficiency of breeding cycles and shortening the time to develop improved varieties.

5. Participatory Breeding and Stakeholder Engagement: Involving farmers, consumers, and other stakeholders in the MAGIC breeding process can ensure that the developed varieties meet their needs and preferences. Participatory breeding approaches can incorporate feedback and input from end-users, resulting in cultivars that are more readily adopted and have improved market acceptance. This engagement can enhance the relevance and impact of MAGIC breeding in addressing specific challenges and market demands.

6. Integration of Omics Technologies: Omics technologies, such as transcriptomics, metabolomics, and proteomics, can be integrated with MAGIC breeding to gain a deeper understanding of the molecular mechanisms underlying complex traits. These technologies can help identify key genes, pathways, and regulatory networks associated with desirable traits. By integrating omics data with the genetic and phenotypic information from MAGIC populations, breeders can unravel the biological basis of traits and accelerate trait improvement.

7. Crop-Specific Applications: MAGIC breeding can be further tailored to specific horticultural crops, taking into account their unique characteristics and breeding goals. Crop-specific applications can focus on addressing crop-specific challenges, such as post-harvest traits, flavor improvement, specific disease resistances, or nutritional enhancements. By aligning MAGIC breeding strategies with the specific needs and priorities of individual horticultural crops, breeders can maximize the impact and success of the approach.

In conclusion, the future of MAGIC breeding in horticultural crops lies in expanding genetic diversity, advancing phenotyping and genotyping technologies, integrating genomic selection and prediction, engaging stakeholders, leveraging omics technologies, and tailoring the approach to specific crops. These prospects and directions hold significant promise for accelerating the development of improved horticultural varieties with enhanced agronomic traits, resilience, and market suitability.

## 8. Conclusion

This review provides a comprehensive overview of the principles, applications, and advantages of MAGIC breeding in horticultural crops. By harnessing genetic diversity and combining parental lines, MAGIC breeding offers a promising approach for crop improvement. It has the potential to enhance genetic variation, improve yield, quality, and disease resistance, and provide novel gene combinations. While challenges and limitations exist, current progress and success stories demonstrate the effectiveness of MAGIC breeding. Future prospects lie in integrating genomic tools, multi-trait selection, expanding to underutilized crops, and utilizing biotechnology approaches. MAGIC breeding holds immense potential to revolutionize horticultural crop improvement and contribute to sustainable agriculture in the future.

## 9. References


Agostino, D.N., Tripodi, P., 2017. NGS-based genotyping, high-throughput phenotyping and genome-wide association studies laid the foundations for next-generation breeding in horticultural crops. Diversity 9(3), 38.

Arrones, A., Vilanova, S., Plazas, M., Mangino, G., Pascual, L., Diez, M.J., Gramazio, P. 2020. The dawn of the age of multi-parent MAGIC populations in plant breeding: Novel powerful next-generation resources for genetic analysis and selection of recombinant elite material. Biology, 9(8), 1–25.

Bandillo, N., Raghavan, C., Muyco, P.A., Sevilla, M.A.L., Lobina, I.T., Ermita, C.J., 2013. Multi-parent advanced generation inter-cross populations in rice: progress and potential for genetics research and breeding. Rice 6, 1–15.

Barchi, L., Acquadro, A., Alonso, D., Aprea, G., Bassolino, L., Demurtas, O.2019. Single Primer Enrichment Technology (SPET) for high-throughput genotyping in tomato and eggplant germplasm. Frontiers in Plant Science 10(1005), 1–17.

Bennurmath, P., Kumar, R., Nair, S. A., Venugopalan, R., Laxman, R.H., 2022. Studies on genetic variability, heritability, correlation and path analysis in chrysanthemum (*Dendranthema grandiflora* Tzvelev). International Journal of Bio-resource and Stress Management 13(3), 213–218.

Bus, V.G., Bowen, J.K., Patocchi, A., Broggini, A.L., Kumar, S., Laurens, F.N., 2019. Breeding fruit cultivars with durable disease resistance in integrated management of diseases and insect pests of tree fruit, Burleigh Dodds Science Publishing, United Kingdom.

Butron, A., Santiago, R., Cao, A., Samayoa, L.F., Malvar, R.A., 2019. QTLs for resistance to fusarium ear rot in a multiparent advanced generation intercross (MAGIC) maize population. Plant disease 103(5), 897–904.

Camargo, A.V., Mott, R., Gardner, K.A., Mackay, I.J., Corke, F., Doonan, J.H., Bentley, A.R., 2016. Determining phenological patterns associated with the onset of senescence in a wheat MAGIC mapping population. Frontiers in Plant Science 7, 1–12.

Campanelli, G., Sestili, S., Acciarri, N., Montemurro, F., Palma, D., Leteo, F., Beretta, M., 2019. Multi-parental advances generation inter-cross population, to develop organic tomato genotypes by participatory plant breeding. Agronomy 9(3), 1–13.

Can, H., Kal, U., Ozyigit, I.I., Paksoy, M., Turkmen, O., 2019. Construction, characteristics and high throughput molecular screening methodologies in some special breeding populations: a horticultural perspective. Journal of Genetics 98, 1–19.

Cavanagh, C., Morell, M., Mackay, I., Powell, W., 2008. From mutations to MAGIC: resources for gene discovery, validation and delivery in crop plants. Current Opinion in Plant Biology 11(2), 215–221.

Chapman, S.C., 2008. Use of crop models to understand genotype by environment interactions for drought in real-world and simulated plant breeding trials. Euphytica 161(1–2), 195–208.

Cockram, J., Mackay, I., 2018. Genetic mapping populations for conducting high-resolution trait mapping in plants. Plant Genetics and Molecular Biology, 109–138.

Colley, M.R., Dawson, J.C., McCluskey, C., Myers, J.R., Tracy, W.F., van Bueren, E.L., 2021. Exploring the emergence of participatory plant breeding in countries of the Global North-a review. The Journal of Agricultural Science 159(5–6), 320–338.

Dell'Acqua, M., Gatti, D.M., Pea, G., Cattonaro, F., Coppens, F., Magris, G., Hlaing, A.L., Aung, H.H., Nelissen, H., Baute, J., Frascaroli, E., 2015. Genetic properties of the MAGIC maize population: a new platform for high-definition QTL mapping in Zea mays. Genome Biology 16(1), 1–23.

Dinesh, M.S., Delvadiya, I.R., Duluri, S., 2023. Enchanting insights and exploring the relevance of the magic population in advancing cereal crop improvement. International Journal of Plant & Soil Science 35(17), 162–178.

Ebert, A.W., 2020. The role of vegetable genetic resources in nutrition security and vegetable breeding. Plants 9(6), 736.

Gaur, P.M., Samineni, S., Thudi, M., Tripathi, S., Sajja, S.B., Jayalakshmi, V., Mannur, D.M., Vijayakumar, A.G., Ganga Rao, N.V., Ojiewo, C., Fikre, A., 2019. Integrated breeding approaches for improving drought and heat adaptation in chickpea (*Cicer arietinum* L.). Plant Breeding 138(4), 389–400.

Giridhar, K., Kumari, S.S., Babu, K.N., Thankamani, C.K., Sastry, E.V.D., Singh, D., Patel, R., 2016. Mega environment analysis and cultivar selection for resource optimization. International Journal of Bio-resource and Stress Management 7(4), 798–806.

Grattapaglia, D., 2022. Twelve years into genomic selection in forest trees: climbing the slope of enlightenment of marker assisted tree breeding. Forests 13(10), 1554.

Gurung, A., Kumar, R., Aswath, C., Prakash, T., Bennurmath, P., Manamohan, M., Reddy, D.C., 2022. Characters association and path coefficient analysis among quantitative traits of chrysanthemum (Dendranthema× Grandiflora tzvelev). International Journal of Bio-resource and Stress Management 13(12), 1411–1416.

Hickey, S., Mohan, G., 2005. Relocating participation within a radical politics of development. Development and Change 36(2), 237–262.

Hoagland, L., Navazio, J., Zystro, J., Kaplan, I., Vargas, J.G., Gibson, K., 2015. Key traits and promising germplasm for an organic participatory tomato breeding program in the US midwest. HortScience 50(9), 1301–1308.

Huang, B.E, Verbyla, K.L, Verbyla, A.P, Raghavan, C., Singh, V.K., Gaur, P., 2015. MAGIC populations in crops: current status and future prospects. Theoretical and Applied Genetics 128, 999–1017.

Hufford, M.B., Berny Mier y Teran, J.C., Gepts, P., 2019. Crop biodiversity: an unfinished magnum opus of nature. Annual Review of Plant Biology 70, 727–751.

Huynh, B.L., Ehlers, J.D., Huang, B.E., Munoz-Amatriain, M., Lonardi, S., Santos, J.R., Roberts, P.A. 2018. A multi-parent advanced generation inter-cross (MAGIC) population for genetic analysis and improvement of cowpea (*Vigna unguiculata* L. Walp.). The Plant Journal 93(6), 1129–1142.

Ibrahim, A.K., Zhang, L., Niyitanga, S., Afzal, M.Z., Xu, Y., Zhang, L., Zhang, L., Qi, J., 2020. Principles and approaches of association mapping in plant breeding. Tropical Plant Biology 13, 212–224.

Janila, P., Variath, M.T., Pandey, M.K., Desmae, H., Motagi, B.N., Okori, P., Manohar, S.S., Rathnakumar, A.L., Radhakrishnan, T., Liao, B., Varshney, R.K., 2016. Genomic tools in groundnut breeding program: status and perspectives. Frontiers in Plant Science 7, 289.

Jimenez-Galindo, J.C., Malvar, R.A., Butron, A., Santiago, R., Samayoa, L.F., Caicedo, M., Ordas, B., 2019. Mapping of resistance to corn borers in a MAGIC population of maize. BMC Plant Biology 19, 1–17.

Johal, G.S., Balint-Kurti, P., Weil, C.F., 2008. Mining and harnessing natural variation: a little MAGIC. Crop Science 48(6), 2066–2073.

Kover, P.X., Valdar, W., Trakalo, J., Scarcelli, N., Ehrenreich, I.M., Purugganan, M.D., 2009. A multiparent advanced generation inter-cross to fine-map quantitative traits in Arabidopsis thaliana. PLoS Genetics 5(7), 1–15.

Kushanov, F.N., Turaev, O.S., Ernazarova, D.K., Gapparov, B.M., Oripova, B.B., Kudratova, M.K., Rafieva, F.U., Khalikov, K.K., Erjigitov, D.S., Khidirov, M.T., Kholova, M.D., 2021. Genetic diversity, QTL mapping, and marker-assisted selection technology in cotton (*Gossypium* spp.). Frontiers in Plant Science 12, 779386.

Li, X., Li, H., Zou, Q., Li, Z., Wang, M., Xu, C., 2014. What has been neglected in the green revolution? Developing crop poly-genotype varieties for improving (intra-variety) genetic diversity in agriculture. Open Journal of Ecology 4(07), 394.

Lopez-Malvar, A., Malvar, R.A., Butron, A., Revilla, P., Pereira-Crespo, S., Santiago, R., 2021. Genetic dissection for maize forage digestibility traits in a multi-parent advanced generation intercross (MAGIC) population. Agronomy 11(1), 1–13.

Mukankusi, C., Raatz, B., Nkalubo, S., Berhanu, F., Binagwa, P., Kilango, M., Williams, M., Enid, K., Chirwa, R., Beebe, S., 2019. Genomics, genetics and breeding of common bean in Africa: A review of tropical legume project. Plant Breeding 138(4), 401–414.

Narayanasamy, N., 2009. Participatory rural appraisal: Principles, methods and application. SAGE Publications Ltd.

Neef, A., Neubert, D., 2011. Stakeholder participation in agricultural research projects: a conceptual framework for reflection and decision-making. Agriculture and Human Values 28, 179–194.

Nkomo, G.V., Sedibe, M.M., Mofokeng, M.A., 2021. Production constraints and improvement strategies of cowpea (*Vigna unguiculata* L. Walp.) genotypes for drought tolerance. International Journal of Agronomy, 1–9.

Oconnor, L.J., Schoech, A.P., Hormozdiari, F., Gazal, S., Patterson, N., Price, A.L., 2019. Extreme polygenicity of complex traits is explained by negative selection. The American Journal of Human Genetics 105(3), 456–476.

Ongom, P.O., Ejeta, G., 2018. Mating design and genetic structure of a multi-parent advanced generation intercross (MAGIC) population of sorghum (*Sorghum bicolor* (L.) Moench). G3: Genes, Genomes, Genetics, 8(1), 331–341.

Pascual, L., Desplat, N., Huang, B.E., Desgroux, A., Bruguier, L., Bouchet, J.P., Causse, M., 2015. Potential of a tomato MAGIC population to decipher the genetic control of quantitative traits and detect causal variants in the resequencing era. Plant Biotechnology Journal 13(4), 565–577.

Phan, N.T., Sim, S.C., 2017. Genomic tools and their implications for vegetable breeding. Horticultural Science and Technology 35(2), 149–164.

Prohens, J., Gramazio, P., Plazas, M., Dempewolf, H., Kilian, B., Díez, M.J., Fita, A., Herraiz, F.J., Rodríguez-Burruezo, A., Soler, S., Knapp, S., 2017. Introgressiomics: a new approach for using crop wild relatives in breeding for adaptation to climate change. Euphytica 213, 1–19.

Ravi, Y., Narayanpur, V. B., Gangadharappa, P. M., Hiremath, J. S., Shantappa, T., Prashant, A., Doddamani, M.B., 2022. Performance evaluation of ginger genotypes on their yield and nutrient uptake under the coastal Karnataka, India. International Journal of Bio-resource and Stress Management 13(6), 630–637.

Renzi, J.P., Coyne, C.J., Berger, J., Wettberg, E., Nelson, M., Ureta, S., Brus, J., 2022. How could the use of crop wild relatives in breeding increase the adaptation of crops to marginal environments. Frontiers in Plant Science 13, 1–21.

Roy, S.C., Shil, P., 2020. Assessment of genetic heritability in rice breeding lines based on morphological traits and caryopsis ultrastructure. Scientific Reports 10, 1–17.

Sahu, J.K., Sharma, G., Nair, S.K., Netam, N., 2018. Character association and path coefficient analysis in African Marigold (*Tagetes erecta* L.). International Journal of Bio-resource and Stress Management 9(3), 402–407.

Saidaiah, P., Pandravada, S.R., Geetha, A., 2021. Per se performance and variability in dwarf roselle germplasm for yield and yield attributing traits. International Journal of Bio-resource and Stress Management 12(4), 271–277.

Saisupriya, P., Saidaiah, P., Pandravada, S. R. 2022. Analysis of genetic variability, heritability and genetic advance for yield and yield related traits in chilli (*Capsicum annuum* L.). International Journal of Bio-resource and Stress Management 13(4), 387–393.

Samantara, K., Reyes, V.P., Agrawal, N., Mohapatra, S.R., Jena, 2021. Advances and trends on the utilization of multi-parent advanced generation intercross (MAGIC) for crop improvement. Euphytica 217(10), 1–18.

Scott, M.F., Ladejobi, O., Amer, S., 2020. Multi-parent populations in crops: a toolbox integrating genomics and genetic mapping with breeding. Heredity 125, 396–416.

Septiani, P., Lanubile, A., Stagnati, L., Busconi, M., Nelissen, H., Pe, M.E., Marocco, A., 2019. Unravelling the genetic basis of Fusarium seedling rot resistance in the MAGIC maize population: novel targets for breeding. Scientific Reports 9(1), 1–10.

Sharma, M., Singh, Y., Singh, S.K., Dhangrah, V.K., 2016. Exploitation of gynoecious lines in cucumber (*Cucumis Sativus* L.) for heterosis breeding. International Journal of Bio-resource and Stress Management 7(2), 184–190.

Singh, Deo, B., Singh, A.K., 2015. Marker-assisted plant breeding: principles and practices, Springer, 978–981. Available at: https://link.springer.com/book/10.1007/978-81-322-2316-0.

Singh, P., Narayanan, S.S., 2009. Biometrical techniques in plant breeding. 4th edition. Kalyani Publication, New Delhi.

Singh, R.K., Singh, C., Chandana, B.S., Mahto, R.K., Patial, R., Gupta, A., Kumar, R., 2022. Exploring chickpea germplasm diversity for broadening the genetic base utilizing genomic resourses. Frontiers in Genetics 13, 1–29.

Singh, S., Shrivastav, S.P., 2023. MAGIC populations improved traits and provided different accomplishments. International Journal of Environment and Climate Change 13(9), 2174–2182.

Sinha, P., Singh, V.K., Bohra, A., Kumar, A., Reif, J.C., Varshney, R.K., 2021. Genomics and breeding innovations for enhancing genetic gain for climate resilience and nutrition traits. Theoretical and Applied Genetics 134(6), 1829–1843.

Sogbohossou, E.O., Achigan-Dako, E.G., Maundu, P., Solberg, S., Deguenon, E., Mumm, R.H., Hale, I., Van Deynze, A., Schranz, M.E., 2018. A roadmap for breeding orphan leafy vegetable species: a case study of *Gynandropsis gynandra* (Cleomaceae). Horticulture Research 5(2), 1–15.

Srinivasan, S., Sobhan, S.S., Mondal, B., Chand, U., Thudi, M., Varshney, R., Gaur, P., 2021. MAGIC lines in chickpea: development and exploitation of genetic diversity. Euphytica 217(7), 1–137.

Stadlmeier, M., Hartl, L., Mohler, V., 2018. Usefulness of a multiparent advanced generation intercross population with a greatly reduced mating design for genetic studies in winter wheat. Frontiers in Plant Science, 9, 1–12.

Stadlmeier, M., Hartl, L., Mohler, V., 2018. Usefulness of a multiparent advanced generation intercross population with a greatly reduced mating design for genetic studies in winter wheat. Frontiers in Plant Science 9, 1825.

Teja, R.R., Saidaiah, P., Kumar, A.K., Bhasker, K., Geetha, A., 2023. Assessment of genetic variability for yield, yield attributing and quality traits of promising genotypes of cluster bean [*Cyamopsis tetragonaloba* L. Taub.]. International Journal of Bio-resource and Stress Management 14(4), 622–628.

Varshney, R.K., Dubey, A., 2009. Novel genomic tools and modern genetic and breeding approaches for crop improvement. Journal of Plant Biochemistry and Biotechnology 18, 127–138.

Verbyla, A.P., George, A.W., Cavanagh, C.R., Verbyla, K.L., 2014. Whole-genome QTL analysis for MAGIC. Theoretical and Applied Genetics 127, 1753–1770.

Vishwakarma, M.K., Yadav, P.S., Rai, V.P., Kumar, U., Joshi, A.K., 2022. Molecular markers and genomics assisted breeding for improving crop plants. In: Relationship between microbes and the environment for sustainable ecosystem services, Elsevier 1, 303–334.

Wankhade, A.P., Kadirimangalam, S.R., Viswanatha, K.P., Deshmukh, M.P., Shinde, V.S., Deshmukh, D.B., Pasupuleti, J., 2021. Variability and trait association studies for late leaf spot resistance in a groundnut magic population. Agronomy 11(11), 1–13.

Xu, Y., Li, P., Zou, C., Lu, Y., Xie, C., Zhang, X., Olsen, M.S., 2017. Enhancing genetic gain in the era of molecular breeding. Journal of Experimental Botany 68(11), 2641–2666.

Yan, W., Zhao, H., Yu, K., Wang, T., Khattak, A.N., Tian, E. 2020. Development of a multiparent advanced generation intercross (MAGIC) population for genetic exploitation of complex traits in *Brassica juncea*: Glucosinolate content as an example. Plant Breeding 139(4), 779–789.

Zaw, H., Raghavan, C., Pocsedio, A., Swamy, B.M., Jubay, M.L., Singh, R.K., Bonifacio, J., Mauleon, R., Hernandez, J.E., Mendioro, M.S., Gregorio, G.B., 2019. Exploring genetic architecture of grain yield and quality traits in a 16-way indica by japonica rice MAGIC global population. Scientific Reports 9(1), 19605.