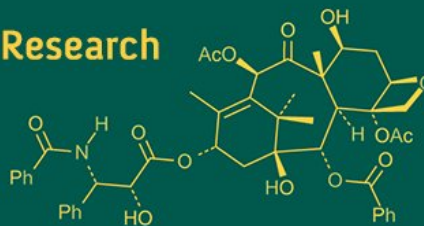
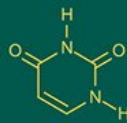


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## Speed breeding in vegetable crops: innovations, applications and future perspectives

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### Abstract

Speed breeding is a new approach to plant breeding that speeds up the crop's generation time based on physical and biological manipulation of growing conditions such as photoperiod, light quality and intensity, temperature, and CO<sub>2</sub> concentration in controlled growing environments. In vegetable crop breeding, where cycles have been traditionally long due to the complex reproductive biology, heterozygosity, and environmental dependency, SB provides a revolutionary pathway for accelerated genetic gain. Recent combination of SB with plant factory, LED-based growth system, genomic selection, CRISPR/Cas genome editing, and AI-based phenotyping has turned it into an advanced "Breeding 4.0" ideology. In this review, we discuss in depth physiological principles of speed breeding, technology innovations, specific applications, advantages, limitations, and future prospects in applications for vegetable crops. Focus is on how SB contributes to faster genetic gain through increasing generations per year to 3-6 generations per year and hence shortening the time needed to develop a new cultivar by approximately 50-70%. The review additionally outlines challenges such as high operating costs, high variability in genotypic responses, and relatively fewer field validation. Finally, it looks at emerging opportunities such as AI-driven autonomous breeding platforms, vertical farming integration, and climate-resilient breeding systems. Therefore, speed breeding reflects a new norm for vegetable crop breeding, enabling rapid genetic gain through accurate and sustainable breeding systems.

**Keywords:** Speed breeding, vegetable crops, controlled environment agriculture, genomic selection, CRISPR, AI phenotyping

### Introduction

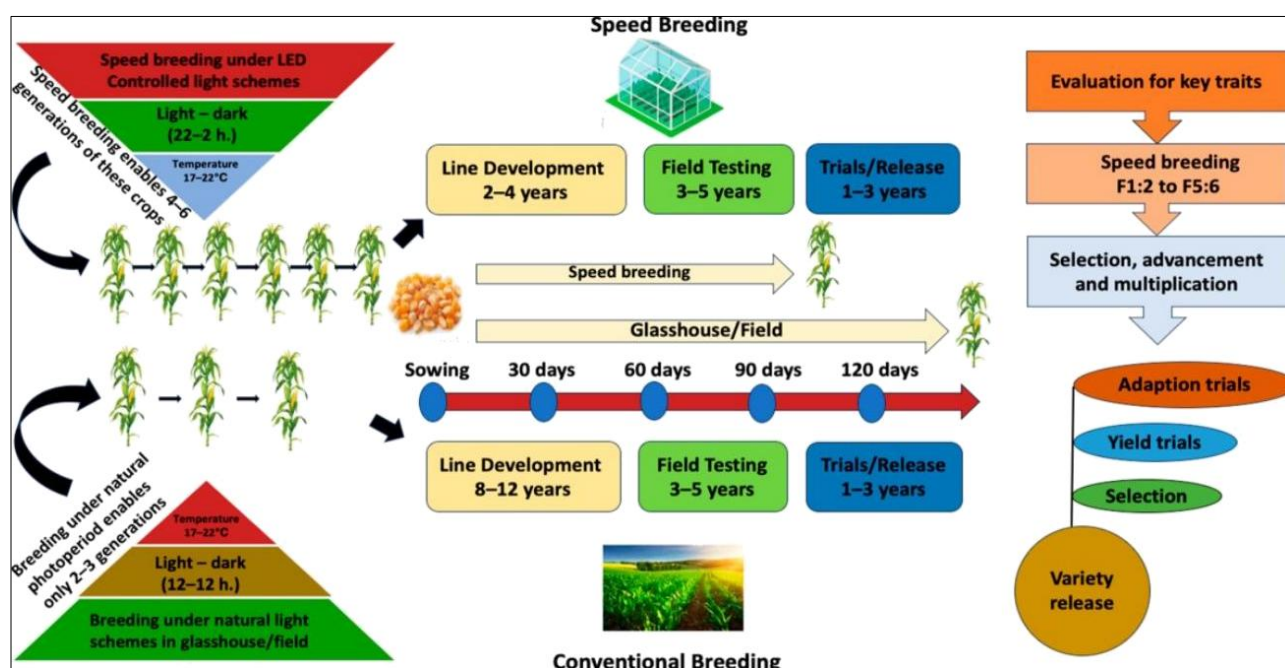
Vegetable crops account for the major share of the human diet and play a key role in ensuring global food and nutrition security, and they provide essential vitamins, minerals, dietary fiber, antioxidants and other bioactive compounds with human health benefits. Besides their dietary value, vegetables are also high value commodities and play an important role in the generation of farm income and rural livelihoods. Yet vegetable cultivation is subject to ever more severe circumstances, including climate change, water deficits, soil fertility loss, reduction of arable land, and novel pest and disease. The rising incidence of extreme events such as drought, flood, and heat wave, have escalated demands for developing resource-efficient, high-yielding, and climate-resilient vegetable cultivars. Therefore, there is a need to enhance the genetic gain, which is a pressing priority for vegetable breeding programmes worldwide (Bevan *et al.*, 2017; Huang *et al.*, 2026) [9, 31]. Traditional vegetable breeding is based on seasonal, field-based selection and evaluation, with only 1 or 2 generations per year in most crops. Thus, the process of breeding a new variety is often a 8- to 12-year or longer journey of recurrent hybridization, selection, selfing, and multilocal testing. Long breeding cycles can restrict the rate of genetic gain and the delivery of cultivars improved for potential new production constraints. To circumvent these constraints, speed breeding (SB) is a revolutionary technique in which plant growth and development, including reproduction, is accelerated by environmental manipulation (photoperiod, temperature, and light quality) in a controlled environment (Watson *et al.*, 2018; Blinkov *et al.*, 2025) [63, 13].

Speed breeding accelerates breeding cycles to multiple generations per year, thus improving breeding efficiency and effectiveness. Although SB was initially brought up for cereal crops, it has more recently been applied to a number of vegetable crops to enable rapid generation turnover, to speed up breeding, to shorten hybrid parent development, and to quickly incorporate disease and stress resistance. In addition, the combination of speed breeding with other emerging technologies like marker-assisted, genomic selection, genome editing, high-throughput phenotyping, and controlled-environment agriculture is shedding light on novel possibilities for rapid crop improvement. These developments make speed breeding a critical asset for developing next generation “Breeding 4.0” systems for producing superior vegetable cultivars tailored for sustainable and climate-resilient agriculture (Hickey *et al.*, 2019; Gao, 2021) [30, 24].

## 2. Concept and Biological Basis of Speed Breeding

### 2.1 Definition of Speed Breeding

Speed breeding (SB) development and convergence of modern technologies such as artificial intelligence, robotics, and gene editing are transforming the future of agriculture and farming. It is executed by manipulating environmental conditions, including photoperiod, temperature, light quality, humidity, and nutrient application, to reduce the time required to flower, develop seeds, and turn over generations. By shortening the crop life cycle, speed breeding allows breeders to obtain multiple generations per year, thus accelerating the development of elite cultivars. Originally designed for use in cereal crops, speed breeding is now being more widely incorporated into vegetable breeding programs to increase rates of genetic gain and to deliver new varieties more rapidly to farmers facing new agricultural challenges (Ghosh *et al.*, 2018; Shiv *et al.*, 2024) [26, 54].



Source: Potts *et al.*, 2023[46]

**Fig 1:** Comparison of Speed Breeding and Conventional Breeding Approaches for Rapid Variety Development and Release

### 2.2 Physiological Principles of Speed Breeding

The speed breeding technique was made possible by modulating a few critical physiological processes that control plant growth and flowering-time. Thus, by providing appropriate environmental conditions, plants can grow faster, flower earlier, and have a shorter life cycle than under traditional field conditions (Xia *et al.*, 2026) [64].

#### (i) Extended Photoperiod

An extended photoperiod (usually 18-22 h light per day) is the most active ingredient of speed breeding. Longer light exposure duration prolongs photosynthesis, increasing carbohydrate production and biomass accumulation. By activating photoperiod-responsive pathways and stimulating photoperiod-dependent flowers induction, it facilitates a quicker switch from vegetative to flowering stage. As a result, extended photoperiods greatly shorten the time to generation turnover and is a key contributor to speed breeding success (Watson *et al.*, 2018; Bhatta *et al.*, 2021) [63, 10].

#### (ii) Optimized Temperature Regime

Temperature is a major determinant of plant metabolism, growth rate and reproductive development. Speed breeding

approaches typically provide a temperature regime of 22-25 °C for the light period and 17-20 °C for the dark period with high humidity and light intensity, which promote rapid development without inducing physiological stress. Proper temperature control promotes photosynthesis, nutrient absorption and cell division, and regulates the development of flower and seed without too early or late. It also enhances pollen fertility, dust formation and seed development, resulting in rapid crop maturation (Mu *et al.*, 2025) [38].

#### (iii) High-Intensity LED Lighting

Contemporary speed breeding protocols depend substantially on LED lighting technology due to its sustainability and ability to deliver tailored light spectra. Specific wavelengths (red, blue, farred light) can be delivered by LEDs and each of these wavelengths has different effects on plant growth. Red light is the most efficient in photosynthesis and flowering, and blue light affects vegetative growth, chlorophyll production and stomata function. The strict control over light quality and quantity brings an exceptional opportunity for breeders to enhance plant growth and development and achieve the highest generation turnaround (Bhattarai *et al.*, 2025; Kabade *et al.*, 2025) [11, 32].

#### (iv) Accelerated Reproductive Transition

One of the main goals of speed breeding is to reduce the duration of the juvenile stage and to promote early flowering. Environmental controlled can enhance the expression of flower related genes such as Flowering Locus T (*FT*), Suppressor of Overexpression of Constans<sup>[1]</sup> (*SOC1*) and Leafy (*LFY*). These genes control the switch from vegetative to reproductive growth and enhance early floral initiation. As plants flower and seed earlier, breeders can move generations faster (Kiss *et al.*, 2025) <sup>[34]</sup>.

#### (v) Continuous and Stress-Free Growth Environment

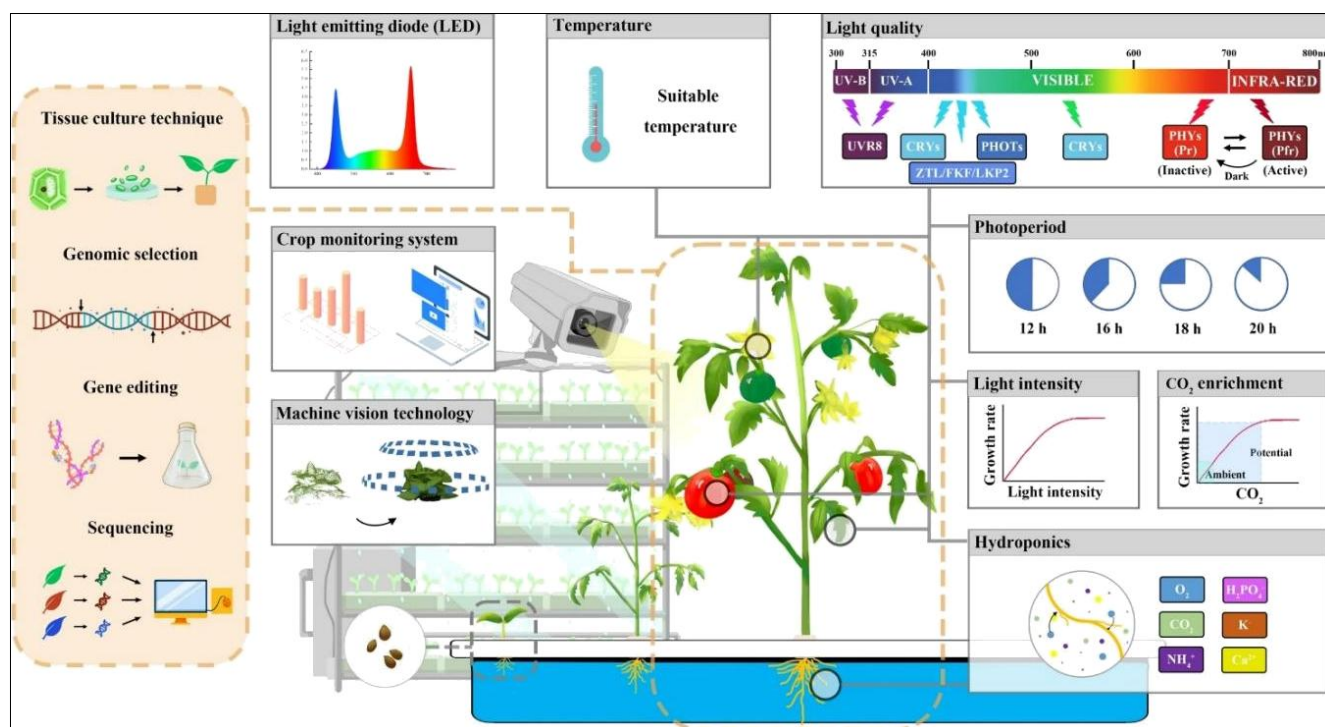
In contrast to open field breeding, speed breeding takes place indoors under controlled conditions, which reduce environmental stresses and seasonal constraints. The plants have a continuous access to water, nutrients, and suitable environmental conditions and are shielded from drought, high temperatures and several pest and diseases. This homogeneous environment allows continual growth and reproduction of the plant to be maintained (up to multiple generations per year) with higher consistency and efficiency (Li *et al.*, 2024) <sup>[37]</sup>.

### 3. Technological Innovations in Speed Breeding

Recent developments in controlled environment agriculture, robotics, molecular biology and information technologies hold great promise for further improving the efficiency and broad applicability of speed breeding. Together these developments have evolved speed breeding from a straightforward modulation of the environment to a holistic breeding approach that facilitates speeding up crop improvement with high selection accuracy. Speed breeding methods utilize sophisticated growing environments with artificial intelligence, genomics and tissue culture methods to substantially increase generation turn over and the overall breeding efficiency (Varshney *et al.*, 2020) <sup>[62]</sup>.

### 3.1 Plant Factory Systems

Plant factories are advanced indoor growing systems that allow for total control of environmental factors, thus being particularly suited for speed breeding and rapid genetic gain in horticultural crops. These system are closed or semi-closed CEA systems, and both systems use: light, temperature, relative humidity (RH), CO<sub>2</sub> concentration, nutrient solution composition and photoperiod to finely tune plant growth and development. Plant factories also add value to breeding by enabling continuous cultivation free from external weather conditions and seasonal limitations (Trivellini *et al.*, 2023) <sup>[61]</sup>. Feature of plant factory is that the vertical multi-layer cultivation systems with the stacking trays of plant culture in multiple layer are used under the artificial lighting systems such as highefficiency light emitting diode (LED), which can dramatically improve the land-use efficiency. This structure not only can enhance efficiency of space productivity, but also assure uniform light distribution that are important for simultaneous growth and induction of flowering. Controlling photoperiod (usually prolonged photoperiod to 18-24 h in speed breeding systems) promotes vegetative growth and reduces generation time, resulting in a greater number of breeding cycles per year (Al Murad *et al.*, 2021) <sup>[4]</sup>. Advanced automated hydroponic, aeroponic or aquaponic delivery of nutrients is now a feature of most modern plant factory systems providing a direct, accurate and uniform flow of water and vital nutrients to the root zone. These hydroculture methods allow for better nutrient-use efficiency, decreases contamination exposure, and facilitate precision management of plant nutrition in support of high biomass production and rapid reproductive transition. Moreover, enhancement of photosynthetic efficiency by application of CO<sub>2</sub> enrichment system is utilized for further acceleration of plant growth under the optimum light and temperature condition (Renganathan *et al.*, 2024) <sup>[50]</sup>.



Source: He *et al.*, 2024<sup>[28, 29]</sup>

**Fig 2:** Integrated Technologies and Controlled Environmental Parameters for Speed Breeding and Precision Crop Production

### 3.2 LED and Smart Lighting Systems

The evolution of programmable LED lighting has emerged as one of the key enablers for speed breeding. In contrast to

traditional lighting systems, LEDs provide the possibility to finely modulate the light intensity, the photoperiod and the spectrum to best fit the needs of the crop. Certain wavelengths,

mainly red and blue light, can be modified to manipulate photosynthesis, flowering, and vegetation. Smart lighting technologies allow breeders to maximize flowering synchrony, increase seed set, and speed plant development. Besides, LEDs are energy-saving, emit less heat and allow more flexibilizations in the design of crop-specific light recipes (Paradiso *et al.*, 2022) <sup>[44]</sup>, thus making them an excellent choice for controlled environment breeding applications.

### 3.3 Artificial Intelligence and IoT Integration

AI and IoT are being adopted more and more in speed breeding under controlled environment to enhance accuracy, automation and effectiveness of decision-making in agriculture controlled environment. Today, in plant factories and growth chambers, IoT-based sensor networks are able to capture myriad environmental and plant parameters of temperature, relative humidity, light intensity and spectra, soil or root-zone moisture, electrical conductivity (EC), pH, nutrient level and atmospheric CO<sub>2</sub> in real-time. These sensors provide a granulated digital profile of the crop microenvironment, allowing for high temporal resolution monitoring of plant growth conditions (Chen *et al.*, 2025) <sup>[16]</sup>.

Artificial Intelligence (AI), machine learning (ML) and deep learning algorithms are used to analyze the large amount of data furnished by IoT systems, which help in discovering intricate patterns and associations among environmental variables and plant developmental responses. These models are capable of predicting notable growth stages like germination, vegetative phase transitions, flowering initiation, and physiological maturity with a great degree of accuracy. Such predictive capability is especially beneficial in speed breeding protocols to maximize generation turnover and potentially synchronize flowering across genotypes (Assimakopoulos *et al.*, 2025) <sup>[8]</sup>.

AI based decision support systems also allow automation of environmental inputs including irrigation schedules, fertigation, photoperiod regulation, spectral light composition (LED tuning), temperature control and CO<sub>2</sub> enrichment. These automated changes happen in real-time without any human interaction, allowing plants to be always grown under the best conditions. For example, AI algorithms can modify R:B (red-blue) LED ratios to enhance flowering or adjust irrigation intervals in response to root-zone moisture variations in real time, leading to improved physiological performance and minimized exposure to (Senoo *et al.*, 2024) <sup>[53]</sup>.

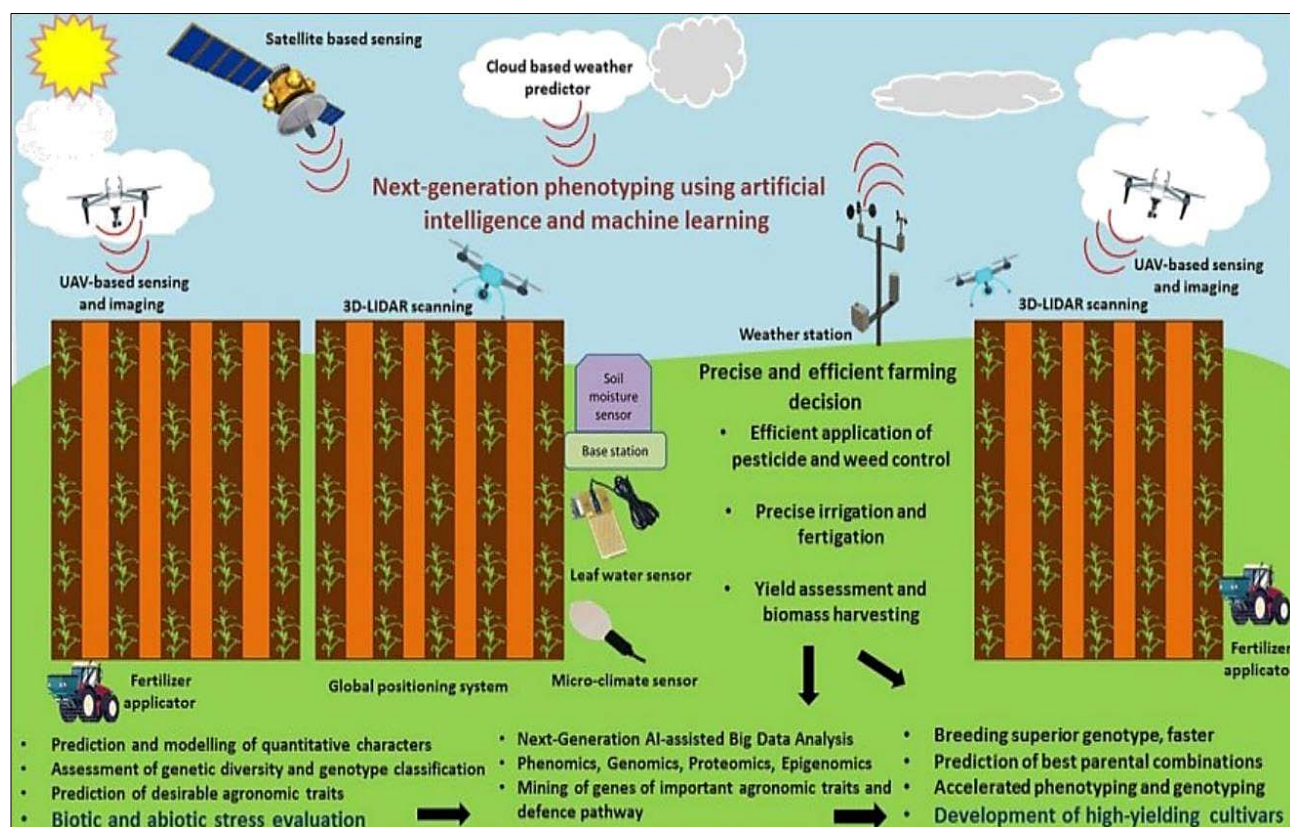


**Fig 3:** Next-Generation Crop Phenotyping Using Artificial Intelligence, Machine Learning, and Precision Farming Technologies

### 3.4 Genomics-Assisted Speed Breeding

The combination of speed breeding and modern molecular breeding methods has revolutionized the rate and accuracy of genetic advancement in crop plants. This integrative method, also known as genomics-assisted speed breeding, integrates the rapid generation turnover in controlled environments with high-density genomic methods to enhance rate of genetic gain per unit time. Although speed breeding hastens by shortening generation times through controlled photoperiod, temperature, and light application and genomic technologies allow selection for more accurate and efficient early more precise

identification of the best genotypes (Ceran *et al.*, 2024) <sup>[14]</sup>.

Core molecular breeding techniques, including marker-assisted selection (MAS), genomic selection (GS) and quantitative trait locus (QTL) mapping, have become indispensable in conventional breeding programs. MAS can identify particular genes or linked markers related to beneficial characteristics such as resistance to disease or tolerance to abiotic stresses, and also can be used for selection in early generations at seedling stage. Similarly, genomic selection exploits genome-wide marker data to estimate genetic values of candidates without phenotypic completion, potentially

shortening the breeding cycle length by a large proportion when combined with speed breeding systems (Sun *et al.*, 2025) <sup>[58]</sup>.

The resolution and throughput of genome analysis have been further improved by recent developments in next-generation sequencing and high-density genotyping arrays. These techniques allow a rapid whole genome scan for favorable alleles linked to complex quantitative traits for example, yield, fruit quality, shelf life and nutrient content. In conjunction with speed breeding, these genomic resources will enable several cycles of selection per year, resulting in greatly accelerated genetic gain in vegetable crops (Ronne *et al.*, 2024) <sup>[18]</sup>.

### 3.5 *In Vitro* and Embryo Rescue Techniques

Tissue culture-based biotechnological approaches also have a strong supportive role in modern speed breeding systems through rapid generation advancement, breaking of reproductive barriers and enabling production of genetically enhanced vegetable crops. These *in vitro* procedures prove to be extremely useful in cases where traditional breeding is hindered by incompatibility barriers, lengthy generation times, poor seed viability, or low hybrid recovery (Saxena *et al.*, 2026; Blinkov *et al.*, 2025) <sup>[52, 13]</sup>.

Among them, embryo rescue technique has become the most popular post fertilization incompatibility overcoming tool. In wide crossing, hybrid embryos frequently die at an early stage of development due to genetic and physiological (or cytoplasmic) incompatibility between parental species or distant genotypes. Embryo rescue allows for the removal of immature embryos at an early stage of development and their subsequent aseptic culture on nutrient media in a controlled environment. This method leads to a successful retrieval of hybrid plants that would be lost otherwise, thus broadening the genetic pool available for improvement of vegetable crops. It has utmost significance in crops like tomato, pepper, Brassica species and cucurbits, where interspecific hybridization is the most common practice to introgress any trait including disease resistance and abiotic stress tolerance (Sinkar *et al.*, 2025; Rogo *et al.*, 2023) <sup>[56, 51]</sup>.

## 4. Applications of Speed Breeding in Vegetable Crops

Utilization of speed breeding technology in vegetable crops has become popular lately as it has potential to speed up genetic gain and shorten the time of cultivar development. Speed breeding allows rapid cycling of generations, speeding up the improvement of breeding populations and the fixation of desirable traits, and enabling the efficient creation of superior cultivars. Its combination with contemporary breeding tools significantly extended the field of application of vegetable crops (Xu, *et al.* 2020) <sup>[65]</sup>.

### 4.1 Speed Breeding in Solanaceous Vegetables

Solanaceous crops like tomato, brinjal (eggplant), and capsicum are among the most widely cultivated and traded vegetables in the world. Development of new cultivars of these crops through conventional breeding is usually time-consuming process. Speed breeding is highly efficient for generation pushing and breeding cycle shortening in these crops (Ding *et al.* 2026) <sup>[20]</sup>. Breeders can efficiently develop highly homozygous lines (generally F<sub>6</sub> – F<sub>8</sub>) from early segregating generations in a matter of months under controlled environmental conditions, which greatly accelerates the timeline as compared to traditional methods. Speed breeding enables the introgression of disease resistance genes to major

pathogens including bacterial wilt, late blight, Fusarium wilt, and viral diseases. In addition, it allows the faster stabilization of the parental lines utilized in hybrid breeding programmes, therefore reducing the time for hybrid creation. It has been reported that in tomato, breeding cycles of 8-10 years can be shortened to about 3-4 years through the use of speed breeding protocols (Muthurajan *et al.*, 2025) <sup>[39]</sup>.

### 4.2 Speed Breeding in Cucurbitaceous Vegetables

Cucurbit crops such as cucumber, melon, pumpkin, bottle gourd, bitter melon, and squash tend to have long breeding cycles due to rampant vegetative growth and late flowering. Speed breeding provides exciting potential for further accelerating breeding gains in these crops through induction of early flowering and rapid seed production (Duan *et al.*, 2025) <sup>[23]</sup>. The technology allows for the development of pure lines by rapid cycling of selfing and generation advancement, thus enabling breeders to realize homozygosity at a faster rate. It also allows for more rapid hybrid seed production by shortening the time to develop parental lines and from through flowering synchronization. In some cucurbit species, controlled environmental factors can induce earlier flowering and fruit set, reducing the duration of the breeding cycle as a whole. Therefore, speed breeding is a potential approach to facilitate the quick generation of high yielding, disease resistant, and quality improved cucurbit cultivars (Niu *et al.*, 2025) <sup>[42]</sup>.

### 4.3 Speed Breeding in Cole Crops

Cabbage, cauliflower, broccoli, Brussels sprouts, and kale are cole crops of the genus Brassica and are the most widely grown vegetable crops worldwide. Vernalization requirements, which hinder flowering and seed production under standard conditions of these crops, also limit breeding improvement (Dieudonne *et al.*, 2025) <sup>[19]</sup>. As speed breeding produces environments which are engineering controlled to achieve fast plant growth and therefore limited plant size, it can be used to overcome these and other limitations. Speed breeding, combined with artificial vernalization procedures, allows for an even earlier reproductive development and a higher rate of generation turnover. The methodology is especially advantageous for speeding up hybrid breeding programs as well as for creating lines with enhanced resistance to diseases, pests, and abiotic stress. Testing can be completed faster and, as a result, stress tolerance breeding and evaluation of traits is more effective under controlled environment conditions for Brassica vegetables (Adhikari *et al.*, 2022) <sup>[1]</sup>.

### 4.4 Speed Breeding in Root and Tuber Vegetables

Root and tuber crops, including carrot, radish, turnip and beetroot, typically have fairly long life cycles, as they flower and set seed only after a large amount of vegetative growth. Speed breeding provides a practical method to shorten the time for reproductive course and seed production in these species (Singh *et al.*, 2025) <sup>[55]</sup>.

The induction and rate of flowering can be high under controlled environmental conditions with a shorter seed maturity time that would allow a faster generation turnover. The technique also enables controlled seed production as well as the rapid identification of superior genotypes for root quality, yield, nutritional value and stress resistance. In radish and carrot, speed breeding may significantly reduce breeding time, so that breeders can perform more selection cycles in a limited time period, leading to faster genetic gain (Xu *et al.*, 2025).

## 5. Integration of Speed Breeding with Modern Breeding Approaches

The leverage breeding speed can provide goes far beyond just speeding up generation time; its main value is realized when it is used in concert with other plant breeding technologies to create a truly efficient, information-based, and precision crop improvement system. In conjunction with advanced genomic, phenomic, and computational approaches, speed breeding serves as a genetic gain multiplier by allowing fast generation turnover and highly accurate identification of superior genotypes. Such a holistic approach started to be considered foundation of next generation breeding platforms especially in vegetable crop improvement in face of evolving climate and agricultural production system (Krishnappa *et al.*, 2021; Pandey *et al.*, 2022) [35, 43].

A major synergy is emerging with genomic selection (GS), the use of genome-wide marker information to predict the breeding values of individuals at young developmental stages. Combined with speed breeding, GS enables several cycles of selection in one year without conducting a full phenotypic evaluation at each generation. This significantly minimizes the length of breeding cycles while holding or potentially enhancing the prediction accuracy for complex quantitative traits like yield, fruit quality or stress tolerance (Yoosefzadeh *et al.*, 2025) [67].

In the same way, the combination of speed breeding with CRISPR/Cas-based genome editing systems has transformed targeted crop improvement. Through genome editing, it is possible to specifically alter genes responsible for important agronomic traits, such as resistance to diseases and abiotic stresses, regulation of flowering time and nutritional quality. By speeding up generations, speed breeding facilitates the fixation and validation of edited alleles, dramatically reducing the time needed to produce stable edited lines amenable to varietal development and release (Chen *et al.*, 2019; Khan *et al.*, 2023) [17, 33].

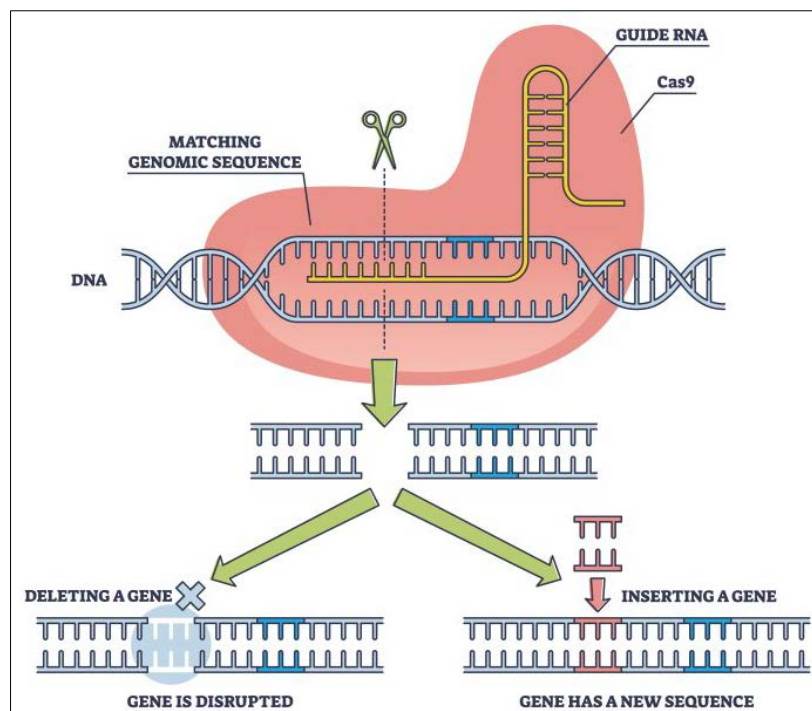
### 5.1 Genomic Selection (GS)

The use of genome-wide marker information to predict genetic values is a new breeding strategy that allows selection of

candidates without phenotypic measurement. Rather than tracing the influence of a small number of loci as in standard MAS, GS models the effects of all available markers distributed throughout the entire genome (Alemu *et al.*, 2024; Lee *et al.*, 2024) [5, 36]. Thus, the synergistic application of speed breeding and genomic selection can provide a more profound improvement in breeding efficiency by integrating rapid generation turnover with early generation selection with high accuracy. Since speed breeding allows several generations within a year, breeders are able to screen and choose the best genotypes on a more regular basis, and thus the genetic accomplishment can be accelerated. This is especially true for complex quantitative traits such as yield, quality, stress tolerance, nutrient-use efficiency, which are controlled by multiple genes. As a result, combining GS with speed breeding leads to shortened breeding cycles and enhanced selection accuracy and overall breeding pipeline (Raza *et al.*, 2025) [49].

### 5.2 CRISPR/Cas Genome Editing

Genome editing tools, notably the CRISPR/Cas system, have transformed the landscape of crop breeding due to their capability to perform precise alterations in target genes linked to key agronomic traits. Nevertheless, gene edited lines often require many generations to be stabilized, have unwanted genetic elements removed and phenotypic expression confirmed (Soyk *et al.*, 2025) [57] after editing. Speed breeding acts as a facet of CRISPR/Cas based genome editing methods by enabling edited plants to be bred over multiple generations at a faster pace. Breeders can rapidly stabilize the resulting genetic modifications and recover homozygous edited lines, as controlled environments facilitate rapid flowering and seed set. This shortens the period required for phenotyping trait, functionally characterizing the gene, and developing variety, significantly. The combination of speed breeding and genome editing appears to be a particularly attractive strategy for breeding enhanced disease resistance, quality and abiotic stress tolerance in vegetable crops (Nasti *et al.*, 2021; Tiwari *et al.*, 2023) [40, 60].



Source: <https://labassociates.com/crispr-a-gene-editing-tool>

**Fig 4:** Mechanism of CRISPR–Cas9-Mediated Gene Editing for Gene Deletion and Insertion

### 5.3 High-Throughput Phenotyping

HTP refers to exploitation of recent advances in imaging and sensor technologies combined with automated analysis to measure plant traits rapidly, nondestructively and repetitively in the same plant over time. Phenotyping accuracy is often a limiting factor in breeding programme, because conventional methods for assessing traits are laborious, slow and prone to human error (Rathore *et al.*, 2026; Du *et al.*, 2020) <sup>[48, 22]</sup>. In combination with speed breeding, HTP platforms facilitate the early selection among very large breeding populations grown under controlled environments. These varying platforms are digital imaging systems, multispectral and hyperspectral sensors, thermal cameras, indoor drone-based imaging platforms, and an artificial intelligence-driven image analysis application (Chang *et al.*, 2021) <sup>[15]</sup>. Such platforms are capable of tracking plant development growth, plant biomass accrual, canopy architecture, physiological status, and symptoms of stress at a pace comparable to that of non-destructive methodology. The information obtained allows for more accurate selection of superior genotypes, and thus an improved breeding efficiency and accelerated genetic gain (Yang *et al.*, 2026) <sup>[66]</sup>.

### 5.4 Integration with Climate-Smart Agriculture

The impact of climate change now represents one of the major threats to world vegetable production with the breeding of climate-resilient cultivars with yield stability under unfavourable environmental conditions being essential. Speed breeding is a great tool for the development of climate-smart varieties through rapid screening and selection using simulated stress conditions (Han *et al.*, 2026) <sup>[27]</sup>. Growth chambers can be programmed to simulate certain stress conditions, including high temperature, water stress, salinity, and high atmospheric CO<sub>2</sub>. This enables breeders to test breeding populations for their potential to perform under future climate conditions and to identify candidates with improved stress tolerance. In conjunction with rapid generation turnover, speed breeding can be used to fast-track breeding of vegetable crops better adapted to environmental change. Hence, it is vital in promoting vegetable production under climate-resilient agriculture and sustainable vegetable production in the era of global climate threats (Angidi *et al.*, 2025) <sup>[7]</sup>.

### 6. Advantages of Speed Breeding

There are many benefits of speed breeding that have led to it being considered a powerful tool for the modern improvement of vegetable crops. One of the main advantages is that it greatly reduces the length of the breeding cycle, which can be twice as fast as with standard breeding techniques leading to a 50-70% reduction in time needed to develop new varieties. Speed breeding can be produced from 3 to 8 generations per year, depending on crop species, by controlling environmental factors, including photoperiod, temperature, and light quality. This quick turnaround in generations means that breeders can more rapidly move populations along their development, go to homozygosity in less time, and have improved cultivars sooner. And since speed breeding is carried out in controlled environments, breeding can be undertaken all year round, free from the limitations of seasons or adverse weather (Garcia-Oliveira *et al.*, 2026) <sup>[25]</sup>.

The fact that speed breeding can increase the general effectiveness of breeding programmes is another vital benefit. Rapid generation advancement leads to rapid development and stabilization of parental lines for hybrid breeding, consequently to shorter time to hybrid cultivar development.

Speed breeding allows for the faster accumulation and testing of disease "resistance traits, breeders to respond more efficiently and timely when faced with new pest and disease threats. Moreover, uniformity of environmental conditions provides greater accuracy in selection as the environmental variance is minimized and assessing breeding materials in a reliable manner is made possible. Therefore, the efficiency of selection is increased and the reliance on long field trials during the initial stage of breeding is decreased (Peng *et al.*, 2026) <sup>[45]</sup>.

### 7. Limitations and Constraints

While the potential of speed breeding is enormous, there exist few bottlenecks that could influence its up-scale adoption and efficacy. A key barrier is the expensive upfront cost for controlled environment systems, such as growth chambers, plant factories and LED lighting systems, as well as climate-control systems. Moreover, the prolonged application of artificial lighting and environmental control system has high energy consumption, which lead to high production expenditure (Shao *et al.*, 2008). One more significant constraint is genotype specificity, since various vegetable species and genotypes may react dissimilarly to prolonged photoperiods and controlled environment, which complicates establishing a general speed breeding routine (Nilsson *et al.*, 2024) <sup>[41]</sup>.

Besides, plants cultured in highly controlled environments do not consistently show the same performance when transplanted into the field environments, causing a potential gap in performance. Thus, field validation is still needed before the cultivar is released. Speed breeding also relies on integrated expertise in plant physiology, controlled environment agriculture, engineering, molecular breeding, and data analytics for its successful adoption. However, these complex technical and resource infrastructure needs may pose a barrier to its use, especially for breeding programmes with limited resources (Thingujam *et al.*, 2025) <sup>[59]</sup>.

### 8. Future Perspectives

The development of speed breeding is inseparable from the development of digital agriculture, automation and biotechnology. Novel AI-based autonomous breeding systems are anticipated to revolutionize breeding programs with machine learning-based trait prediction, automated decision making, and robotics-assisted phenotyping. These technologies will make breeding more precise, less labor-intensive, and subject to fewer human errors. In a similar fashion, the combination of speed breeding and vertical farming systems allow year-round breeding in urban and space constrained environments, providing an opportunity for continuous cultivar development in the tightly controlled environments (Donde *et al.*, 2021) <sup>[21]</sup>.

In addition, speed breeding is anticipated to be integral to developing climate-resilient crops for vegetables that can withstand heat, drought, salinity, and other environmental stressors linked to climate change. In the near future, the Breeding 4.0 paradigm will support speed breeding further by combining genomics, artificial intelligence (AI), robotics, controlled-environment agriculture, and big data science within a single breeding system. This intersection of technologies will facilitate increased genetic gain, selection accuracy, and enable the rapid development of sustainable high-yielding, stress tolerant, and nutritionally enriched vegetable cultivars for the agriculture of the future (Ahmad *et al.*, 2025) <sup>[2]</sup>.

## 9. Conclusion

Speed breeding has become a revolutionary method for fast-tracking enhancement of the vegetable crops by compressing their generation interval and enhancing genetic gain via environmental factor manipulations. Its combination with emerging technology-based plant factory, LED lighting, genomic selection, CRISPR/Cas-based genome editing, high throughput phenotyping, artificial intelligence and IoT has increased the breeding accuracy and efficiency and enabled the rapid generation of high-yielding, disease-resistant and climate-resilient cultivars. Despite limitations such as expensive infrastructures, genotype-dependent responses, and the necessity for validation in the field, further advancements in technology and protocols are expected to enable better scale-up and dissemination. With rising demand for sustainable and climate-smart farming systems, speed breeding is therewith anticipated to be one of the cornerstones of next-generation vegetable breeding, playing a significant role in global food and nutritional security.

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