



Recent Advances in Speed Breeding for Rapid Wheat Development

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Abstract

The development of wheat through speed breeding is now a matter of using an artificial system that changes with the seasons in nature and takes many years for generation turnover, population advancement, and early selection to happen biologically viable again in breeding. It was found out from the pioneer experiments of speed breeding in wheat that applying extra light for longer periods, maintaining normal room temperatures, collecting seeds when they are immature, and employing the single-seed descent approach could make multiplication of generations in a given annum. The current wave of work goes further. It includes speed vernalization techniques for winter wheat; breeder-friendly, low-energy modified glasshouse systems; high-throughput vernalization protocols that are compatible with a wider range of winter germplasm; spectral optimization strategies that tune light intensity and the red: far-red ratio; and close links with marker-assisted backcrossing, genomic selection, doubled haploids, and resistance gene cloning. Speed breeding is therefore no longer just a way to obtain generations quickly; it is changing the whole pipeline through which wheat is developed. This review covers the improvements made in speed breeding for rapid wheat development from 2018 onwards, especially between 2022 and 2025, with a focus on practical application in wheat. It first presents the physiological and engineering foundations of fast generation advance in wheat, and then looks at the new platforms introduced for both spring and winter germplasm. Next, it examines how phenotyping, marker-assisted introgression, genomic prediction, gene discovery, and rapid line fixation have been integrated into speed breeding. In the literature examined, one can see that initially, people thought that the best approach was to accelerate everything to the maximum speed possible, but now they have realized that this approach does not make sense from a biological perspective and is also very difficult to apply. It can be derived from the review that there is a need for speed breeding in wheat programmes, although it should serve as an addition to and not a substitute for field breeding, which can be considered incomplete without it. The review anticipates the following developments: adaptive lighting recipes; improved approaches to dormancy, winter habit; integration; cost-effective; non-specialized facility accessible rapid generation advance even in; digital phenomics predictive breeding; and development of systems.

Keywords: wheat, speed breeding, speed vernalization, genomic selection, marker-assisted backcrossing, rapid generation advance, indoor farming, disease screening

Introduction

Even though wheat is very important for food all over the world and some progress has been made in breeding wheat over time, it is still moving at a biological time scale. It takes quite a while for the effective breeding process to go from selected parents, stable lines, multi-site testing, and finally the release of varieties. The relationship between the crop development calendar and every recombination, segregation, fixation, or evaluation cycle in spring wheat allows only one or two generations annually using the conventional field-based system. In winter wheat, this is made worse by the fact that it takes even longer for crosses to be converted into lines that can be tested in the field due to the requirement for vernalization. These extended cycles reduce yearly genetic

improvement as they increase generation intervals, which is one of the factors that determine response to selection in the breeder's equation along with selection intensity and heritability. Hence, any technology that can reduce the length of the cycle without losing its value for selection would be of great importance in improving wheat (Watson et al., 2018; Bhatta et al., 2021).

The problem led to the development of speed breeding (SB), a method that employs various techniques such as photoperiod manipulation, temperature adjustment, changes in light intensity, altered planting density, and harvest timing to quickly obtain viable seeds of the subsequent generation right after sowing. For instance, in spring wheat, research has

shown that it is possible to have numerous cycles within one year when using extended lighting regimes but still get fertile ears with enough grain for continuing single-seed descent or related inbreeding pipelines. At present, the breeding philosophy goes well beyond the accelerated growth protocol with which it began. It is evident that there is no longer any doubt as to whether it is possible to speed up the growth of wheat in controlled environments. Today, the question is how we can apply this fast growth in order to improve our breeding decisions so as to increase genetic gain and better connect with molecular markers, genomic prediction, as well as targeted gene cloning. (Watson et al., 2018; Pandey et al., 2022; Ceran et al., 2024), and how to ensure that acceleration is applied wisely. The conventional and speed-breeding-enabled pathways are compared in Figure 1.

The first years of speed breeding brought a lot of enthusiasm, but also some concerns. Was the use of long photoperiods practical, given that it could consume much energy? Could the vernalization requirements of different wheat types be met easily by the protocols developed for winter wheat? Did rapid cycling alter important phenotypes? Were seed quantity and quality sufficient for breeding operations at scale? These questions arose with the early protocols, but recent protocols have addressed them more fully (Cha et al., 2023; Li et al., 2025; Dhakal et al., 2025). Developments that have brought speed breeding into actual programs include modified glasshouse units, spectrum-aware lighting recipes, speed vernalization (SV) or high-throughput vernalization (HTV),

and breeder-focused pipelines. Speed breeding is also now used for purposes beyond fast generation turnover, such as rapid disease screening, phenotypic selection, marker-assisted backcrossing, genomic selection, and even cloning of disease resistance genes.

This review examines progress in speed breeding with special emphasis on wheat. It does not consider attempts to accelerate breeding in all crops, but rather the rapid development of wheat. In particular, the review focuses on: **(i)** the physiological aspects that contribute to rapid generation development in wheat; **(ii)** how the initial protocols on the dominant speed breeding platforms have evolved with the advent of new ones, including those for winter wheat and energy-saving measures; **(iii)** whether phenotypes and breeding decisions made under speed breeding conditions remain useful, and what evidence supports this; **(iv)** whether integrating speed breeding with genomic and molecular approaches is feasible; and **(v)** the operational challenges that impede wider use of speed breeding. The literature reviewed ranges from fundamental work done as far back as 2018 up to 2026, although very few studies have appeared this late; particular attention was given to recent primary studies, especially in wheat. In general, the research indicates that merely validating speed breeding as effective is no longer the main focus of the area; rather, it is a crucial aspect in enhancing wheat worldwide. (Wanga et al., 2021; Ceran et al., 2024).

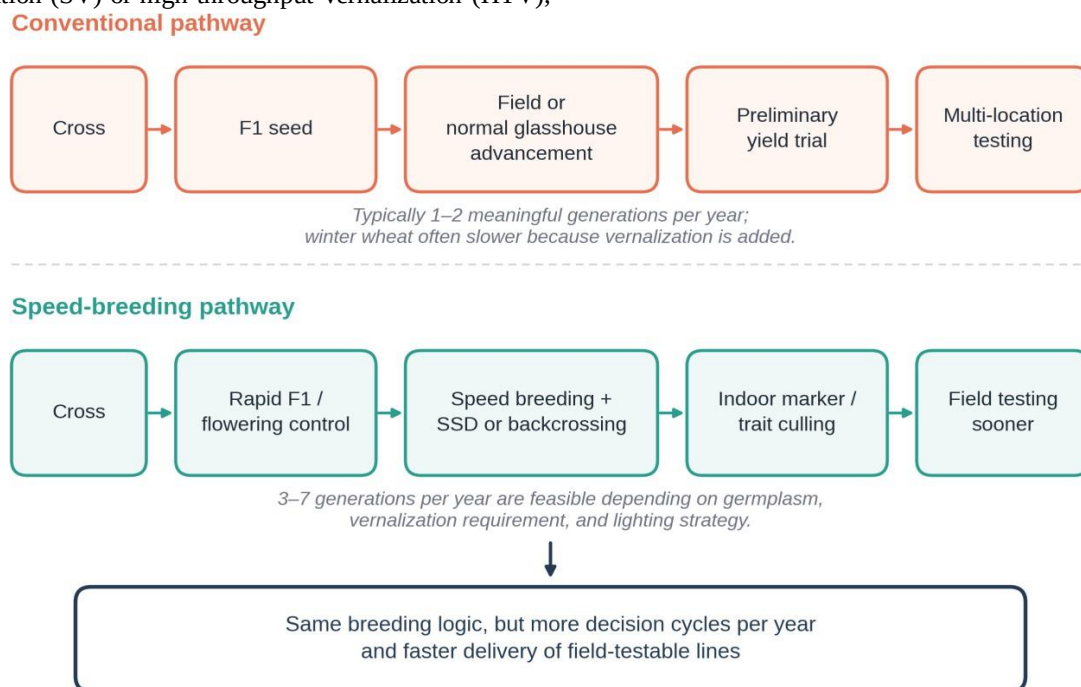


Figure 1. Conceptual comparison of conventional and speed-breeding-enabled wheat development pathways. SSD, single-seed descent.

Scope of the review and conceptual framework

This paper uses the term speed breeding in a broad but focused manner. It means deliberately changing the surroundings to make the time taken from one seed of wheat to another shorter. Practically speaking, this involves using a combination of prolonged photoperiods, optimal temperature regimes, modified light intensities and wavelengths, early seed harvesting, dormancy control, as well as fast generation change techniques. Nonetheless, recent research on wheat shows that speed breeding is most effective when integrated with line fixation, phenotyping, marker-assisted selection, genomic prediction, and targeted introgression. As such, this review considers both the development protocols and the breeding workflows associated with them (Pandey et al., 2022; Ceran et al., 2024).

This review is divided into two parts in a very simple manner. To begin with, there are certain acceleration variables such as photoperiod, temperature, spectrum, vernalization, density, nutrition, and seed-handling interventions that directly affect the length of the cycle. Secondly, translation variables ask whether a fast-growing, healthy-looking plant can provide the breeder with reliable data for selection, crossing, or advancement purposes. This division is significant because the best breeding cycle is different from the shortest cycle. For instance, a plan that saves an additional ten days but results in weak fertility, high lodging, biased disease expression, or increased operating costs may not be beneficial to the overall breeding program. Therefore, one should evaluate the recent breakthroughs to determine whether they enhance both acceleration and translation (Cha et al., 2023; Chhabra et al., 2024).

In the review, we look at the use of wheat across three levels of operation. The first tier involves quick generation advancement for spring or facultative types where vernalization poses little problem. On the other hand, the second tier looks at those winter wheat systems that require accelerating or changing the process of vernalization for better functionality. The final tier focuses on holistic integrated pipelines that contain speed breeding alongside other components such as phenotyping, markers, genomic selection, doubled haploids, or gene discovery. This tiered perspective clarifies the reason why certain protocols are most effective in research populations, some in pre-breeding, while others in regular cultivar development. It also means that no single speed breeding protocol can be regarded as the best solution for all wheat germplasm under every breeding objective (Bhatta et al., 2021; Dhakal et al., 2025).

Physiological and engineering basis of rapid wheat generation advance

Speed breeding is possible because wheat responds strongly to environmental conditions such as light and temperature.

Photoperiod is probably the most important environmental cue (Watson et al., 2018; Ghosh et al., 2018). Although the specific photoperiod responses vary, wheat generally falls into one of two categories: short-day and long-day plants. Most spring wheat varieties are long-day plants; they move from vegetative to reproductive development earlier under extended photoperiods (e.g., >20 hours). For example, when wheat is grown under a 16-hour versus a 22-hour photoperiod, plants under the longer photoperiod produce fewer leaves before the transition, fewer stems elongate (more semi-dwarf growth), and they flower earlier. These differences in the duration of the vegetative phase explain why speed breeders have used extended photoperiods from the start to accelerate flowering.

Extended photoperiod does more than accelerate the reproductive transition. It increases photosynthetic carbon gain, which allows plants to increase leaf number before the reproductive transition and partly compensates for the extra costs imposed by a longer day. However, recent work shows that simply lengthening the photoperiod is not enough to speed-breed wheat; it also reports that suitable “assimilate conditions” are needed to support fertility and seed fill. Light quality has also been neglected in speed breeding. High temperatures also accelerate wheat development, but there is a trade-off: if temperatures become too high, or stay high too long, fertility suffers. A number of successful speed breeding protocols have used day/night temperature regimes with warm (but not hot) days and cool nights. Winter wheat breeders have long used temperature to vernalize their crops: they hold the crop at low (but not too low) temperatures for extended periods until the cold requirement is satisfied. It is a common refrain in speed breeding that spring wheat is much easier to breed and speed-breed than winter wheat, because the latter needs cold temperatures to satisfy its vernalization requirement.

This is now changing. Recent work has shown that warm temperatures (within reason) can speed up vernalization (Cha et al., 2022; Dhakal et al., 2025) if the crop is exposed to long days during its “cold” phase or, better still, to brief exposure of the seed surface to light. This appears to work particularly well with the newest winter wheat varieties. If vernalization can be both accelerated and combined with light at relatively warm temperatures, it helps to overcome one of the major past obstacles to speed breeding, namely speeding up wheat that was bred, or intended for use, in the winter rather than the summer planting window.

In summary, wheat breeders can combine photoperiod manipulation, temperature, and genetics to find a suitable recipe for accelerating their breeding cycle. However, it is important to remember that these three environmental factors (photoperiod, temperature, and irradiation) interact. None of

them has the same effect on development when applied alone; combinations of them, as used in speed breeding or even in a normal glasshouse, may give better results. Irradiation also plays an important role in crop development, and understanding it could have a major impact, as discussed next. Light quality is the third vital component that was overlooked in most of the early speed breeding systems, which focused on photoperiod. Nevertheless, research indicates that developmental rate and yield expression are influenced by spectral composition. In this regard, it has been proven through indoor farming systems that time to anthesis, biomass partitioning, and grain production are dependent on certain factors like color temperature, photon flux density, and dynamic lighting schedules (Denton et al., 2023). For instance, if you decrease the red: far-red ratio, flowering will occur about seven days faster in wheat; but again, this effect might depend on some genotypes or substrates and could interact with mineral nutrition. These discoveries matter since they push speed breeding away from being an unscientific method that depended on increased day lengths towards a well-advanced photobiology-based approach (Li et al., 2025; Nagamova et al., 2025). It follows then that instead of exposing them to maximum, the best should be optimum signaling and energy delivery. The decisions taken by

engineers at the canopy and seed level are very important. These include pot size, rooting volume, substrate composition, fertilizer schedule, and planting density, all of which influence how much cycle compression can proceed before there is a physiological problem. This is because even though high-density single-seed descent is still applicable, as it creates an opportunity for speeding up through thousands of segregants, such dense populations will only thrive under tight nutritional and watering regimes aimed at preventing severe stress-induced seed abortion. Early-stage seed extraction and rapid drying may lead to shortened cycles, but this depends on whether the embryos are sufficiently mature or not. In cases where dormancy occurs, it may help to have a little after-ripening period or germination control for an easy handover of one generation to another. Put simply, speed breeding involves multiple strategies rather than a single one: manipulating developmental physiology, creating favorable microclimates, and managing population logistics. The most recent literature is interesting because it does exactly this; it separates the individual elements and determines which combinations work best in real wheat breeding scenarios (Cha et al., 2023; Li et al., 2025). The main environmental levers are summarized in Figure 2.

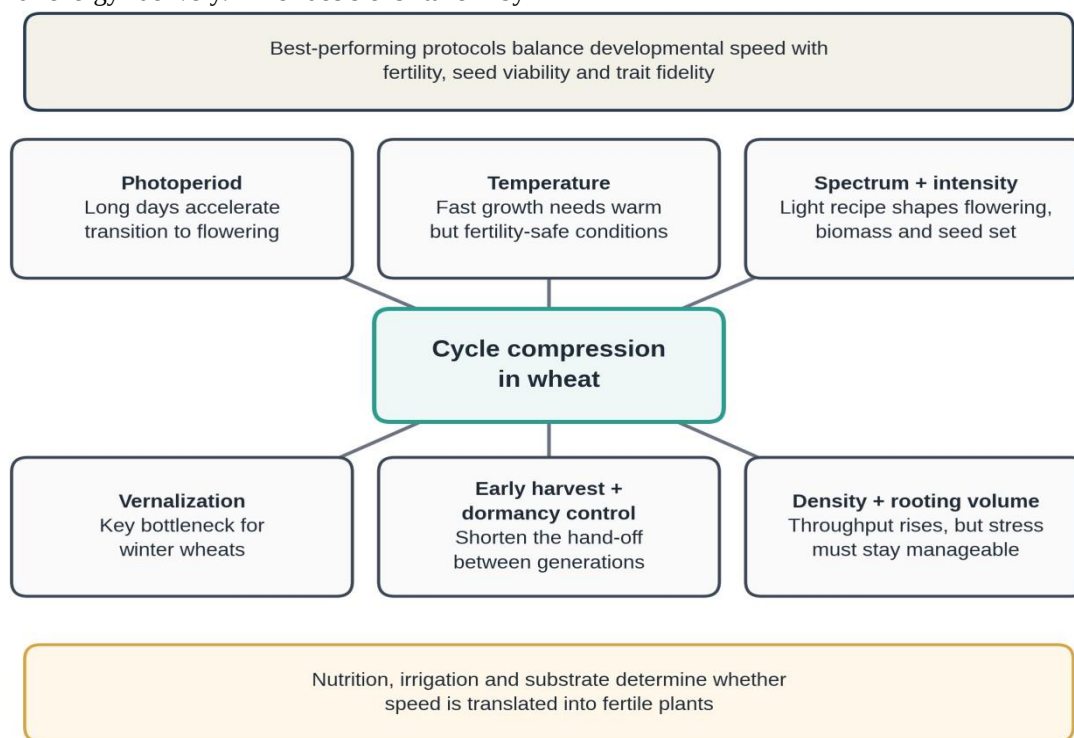


Figure 2. Environmental levers that determine cycle compression in wheat speed breeding.

Evolution of wheat speed-breeding platforms

The first step toward wheat speed breeding in this millennium was the demonstration that cereals mature faster under controlled conditions with extended photoperiod. The initial setup was described by Watson et al. (2018) and later

improved by Ghosh et al. (2018), in which near-continuous daytime lighting, optimal temperature, and quick postharvest handling of seeds allowed the advancement of several spring wheat lines. Certain principles were derived from this work that continue to inform the management of the reproductive

stage in cycled generations: **(1)** speed breeding can be combined with SSD on a large scale, and **(2)** growth chambers, glasshouses, or facilities with supplementary lighting are suitable operating environments. These studies also supported the idea that speed breeding could be incorporated into breeding programs in the same way as in another non-experimental botanical research (Watson et al., 2018; Ghosh et al., 2018).

Practical refinement took center stage in the second phase of development. The first-generation protocols relied on very long hours of artificial lighting, which was expensive to run, and this was seen as a problem. Breeders wanted systems that kept most of the generational gain while using less electricity and fitting more naturally into glasshouse-based workflows. As a result, modifications were introduced to help breeders, in which natural sunlight was used for part of the day, and the rest of the long photoperiod was supplemented with artificial lighting. Of particular significance here is the modified speed breeding system documented in wheat (*Triticum aestivum*) by Zhang et al. (2023). It allowed rapid cycling to continue, with about four generations possible in one year, but at a greatly reduced energy cost compared with the speed vernalization plus speed breeding approach. Equally important, the researchers showed that heading date and culm length in the adjusted environment were correlated with those observed in the field; efficient speed breeding could therefore be both accelerated and widely applicable.

Another track targeted winter wheat. For years, the natural obstacle to acceleration was vernalization, which affects winter cereals but not spring ones. Classical vernalization methods required several weeks of cold exposure, so any time gained later in development could be lost at the start. The opinion on SV was altered since it proved that by subjecting the plants to higher temperatures and longer day lengths at the vernalization stage, most genotypes would complete vernalization quickly and therefore potentially give rise to about five generations of winter wheat in a year under favorable conditions. Nonetheless, even with these advancements, there was still an issue with some genotypes requiring specific amounts of vernalization that could not be overcome easily, especially for those lines exhibiting extremely pronounced winter types. This led to the creation of HTV systems that increased compatibility but still maintained a short annual cycle. Therefore, the development of wheat speed breeding platforms has not been a chain of replacements but rather cumulative. Breeders now have a range of strategies, including the original long-day approach, modified energy-conserving approaches, speed vernalization, and high-throughput winter protocols, which can be matched to germplasm and program objectives (Cha et al., 2022; Cha et al., 2023; Dhakal et al., 2025). The main protocols are compared in Table 1, and the timeline of notable recent advances is given in Table 2.

Protocol/study	Target wheat type	Key environmental features	Indicative cycle advantage	Breeding significance
Foundational SB (Watson et al., 2018)	Spring wheat	22 h light; warm day/cooler night; early seed handling	Up to about 6 generations per year	Established proof of concept for rapid wheat generation advance
Detailed chamber + glasshouse protocol (Ghosh et al., 2018)	Spring wheat and related long-day crops	Operational protocol with chamber and supplemented-glasshouse variants	Standardized rapid cycling across facilities	Turned the concept into a reproducible breeding method
Speed vernalization + SB (Cha et al., 2022)	Winter wheat	Warmer vernalization plus long photoperiod before transfer to SB	Raised winter materials to about 5 generations per year in responsive lines	Removed the classical winter-wheat bottleneck
Modified breeder-friendly SB (Cha et al., 2023)	Spring and adaptable breeding materials	Natural sunlight plus about 12 h LED to complete a 22 h photoperiod	About 4 generations per year with major energy savings	Improved practicality, lower power demand, better fit for routine glasshouse breeding
Indoor light-recipe system (Li et al., 2025)	Spring wheat	Spectrally tuned LEDs, optimized intensity, long photoperiod, dynamic light options	More than 7 generations per year are theoretically achievable in optimized indoor settings.	Shifted emphasis from generic long days to recipe-based photobiology
HTV + shallow planting + SB (Dhakal et al., 2025)	Winter wheat with stronger vernalization needs	High-throughput vernalization followed by SB; shallow sowing accelerated maturity	About 22 days saved per generation versus standard glasshouse handling	Improved compatibility for larger winter-wheat pipelines

Table 1. Major wheat speed-breeding protocols and the design logic behind them.

Year	Representative advance	What changed	Implication for rapid wheat development
2018	Watson et al.; Ghosh et al.	Foundational long-day speed-breeding systems were demonstrated and protocolized for wheat.	Provided the technical base for modern rapid generation advance
2018	Alahmad et al.	Multiple quantitative traits were screened successfully under accelerated conditions.	Showed that speed breeding could support phenotyping as well as line advancement
2019	Watson et al.; Voss-Fels et al.	Conceptual and empirical integration with genomic selection became clearer.	Cycle compression started to be linked directly to annual genetic gain.
2022	Cha et al.	Speed vernalization redesigned winter-wheat acceleration	Winter germplasm moved closer to the pace previously seen only in spring material
2023	Ficht et al.; Schoen et al.; Cha et al.	Winter-photoperiod optimization and breeder-friendly, lower-energy systems were developed.	Rapid cycling became more practical and more relevant to routine breeding.
2024	Batista et al.; Chhabra et al.; Cha et al.	Large spring populations were advanced strategically; disease screening and marker-assisted introgression were accelerated.	Speed breeding began to function as a program-level platform.
2025	Li et al.; Nagamova et al.; Dhakal et al.; Nannuru et al.; Wang et al.	Lighting recipes, far-red tuning, scalable winter protocols, GS simulations, and rapid gene-cloning workflows matured	Current emphasis shifted toward precision acceleration and system integration

Table 2. Timeline of notable recent advances in wheat speed breeding.

Rapid advancement of spring wheat populations

The most evident progress in spring wheat has been the move away from experimental accelerations toward deliberately designed inbreeding pipelines (Watson et al., 2018; Batista et al., 2024). Early speed breeding articles showed that cycles could proceed at high speed in spring wheat, while recent ones explain how to harmonize this acceleration with real breeding-stage decisions. Take, for instance, the 2024 report from Batista and others: It was revealing. In this report, they indicated that by using speed breeding on the segregating F2 spikes of spring wheat, and then taking them through several off-season generations, they were still able to get enough F5:6 for small plot yield tests of a large number of lines. However, they were able to turn around their harvest within 54 days, and on top of that, they could forward test more than one hundred genotypes in just one off-season window. In other words, it shows that speed breeding can be applied in altering the planning of breeding programs; not merely providing evidence for faster plant growth with longer day exposure. This is significant as one can only achieve rapid amalgamation of massive recombinants into stably inheritable lineages fit for replication experiments if they are enhancing spring wheat effectively.

Under normal field conditions, inbreeding usually leaves the breeder with a dilemma: work on a large population and take more time, or work fast with a smaller number of populations. Speed breeding breaks this tie, because it makes continuous single-seed descent or head-row advancement possible at high densities in controlled environments. The program can then keep wide recombination early on, postpone heavy selection until much fixation has been reached, and arrive at

yield trials quickly. Batista et al. (2024) found moderate to high heritability of agronomic traits in subsequent testing, which indicates that rapid off-season pipelines may not necessarily impair downstream selection.

Recent spring wheat research implies that speed breeding is feasible, and that not all generations in a breeding program need to be subjected to the same conditions. For instance, a cross can be made in one environment, the segregating generations advanced quickly using speed breeding, and the material then moved to the field once the lines are stable enough for plot-level evaluation. This staged approach is especially useful where space in controlled environments is very limited, because it directs costly facilities toward the parts of the process where generation time is the biggest problem. It also reduces the likelihood of phenotyping traits in inappropriate environments just because plants happen to be available at the time. These points support a more mature understanding of spring wheat speed breeding: not every indoor selection needs to be perfect; with this technique, the breeder can make up for lost time and reach better selection stages than would be possible with the natural season length alone (Batista et al., 2024; Pandey et al., 2022).

Winter wheat: speed vernalization and high-throughput vernalization

It can be argued that few recent technical breakthroughs in wheat speed breeding are as important as those relating to winter germplasm (Cha et al., 2022; Schoen et al., 2023; Dhakal et al., 2025). Many breeding programs cannot do without winter wheat because it is well adapted, has high yield potential, and carries desirable disease-related traits. Even so, the normal development cycle of winter wheat hinders quick

turnaround in many breeding programs. For a long time, it was assumed that plants undergoing vernalization must be exposed to low temperatures with long hours of darkness for the procedure to be effective and to maximize its effect on developmental stages such as flowering. A turning point came with the “speed vernalization” study by Cha et al. (2022), which is also reviewed here. That study applied elevated temperatures and extended photoperiods during vernalization to speed up the development of winter wheat and barley compared with conventional techniques, and it achieved nearly five generations per year instead of two. This work matters in theory as it proposed that the developmental adaptability of vernalization is not just a matter of a strict cold storage procedure (Cha et al., 2022).

It is important to note that even after the development of the initial speed vernalization systems, the saga continued. These systems needed to be proven effective on various genotypes under near-natural conditions rather than artificial environments used in the initial testing. Follow-up studies plugged this hole. A modified speed breeding study carried out in 2023 indicated that it is possible for breeders to have four generations in a year using the breeder-oriented glasshouse protocols and still consuming very little energy as compared to the control, with acceptable correlation for phenotypic data like heading date and culm length. In translational terms, this was a leap forward. The optimization here did not target maximum speed per se but sought an acceptable compromise between speed, phenotypic relevance, and cost of operation.

Dhakal and his team advanced their research on high-throughput vernalization in 2025. They came up with a plan targeted at winter wheat types that need more vernalization, and that could be used in breeding when working with a large number of lines. According to the research, integration of shallow planting, high-throughput vernalization, and speed breeding can reduce the breeding cycle by approximately 22 days per generation under a standard glasshouse environment as compared to normal conditions. Even though this advantage appears insignificant when related to the normal amplified remarks on speed breeding, it matters greatly in a yearly breeding programme (Dhakal et al., 2025). In winter wheat programs, cutting every reliable week from the cycle could change the number of crosses that reach the field-testing stage within a given period. Importantly, the study also addressed the common complaint that different germplasm does not always respond to a given winter speed breeding protocol in the same way.

Acceleration depends on genotype, as further research on photoperiod and light intensity in winter wheat has shown. In experiments on winter wheat, Ficht et al. (2023) established that photoperiod and lighting affected how soon plants

matured, while in another study on winter cultivars, Schoen et al. (2023) found a considerable further reduction in the time needed to produce one generation. Winter speed breeding can therefore no longer be seen as a specialized offshoot of spring wheat protocols and practices. Evolving, it is becoming a technologically advanced area of great complexity that is distinct from others. It has a unique mode of development, space parameters, and practical guidance that are very complicated (Ficht et al., 2023; Schoen et al., 2023; Dhakal et al., 2025).

Light recipe optimization, energy efficiency, and indoor speed breeding

Wheat speed breeding has fully developed now, with a departure from the use of generic long-day lighting towards specifically tailored artificial lighting, as indicated by Li et al. (2025) and Kabade et al. (2025) studies. Originally, the extended-day approach was employed to accelerate growth within these systems, which was reasonable at the time. With time, however, this initial question has transformed into a much better one: how can one optimize trade-offs between various factors of development like growth rate, seed quality, energy consumption, and fertility? An indoor farming study was carried out by Li et al. (2025), where they assumed a complex manner in which lighting interacts with the environment rather than just turning on/off, as is usually the case with such systems. Their findings indicated that changing the wavelengths of light through different factors, including but not limited to color temperature, photoperiod, photon flux density, as well as dynamic lighting mode, has an influence on wheat flowering time and yield formation itself. Although the authors gave some recommendations of light recipes for over seven generations of annual spring wheat, it also had some reverse effects, such as highest yield per plant versus fastest cycle, among others.

The importance of this work lies in how it substitutes the concept of “continuous or near-continuous light” with an “information-rich lighting strategy,” as discussed by Li et al. (2025). It is harmful to the yield of seeds but can be equally effective as continuous light in promoting development at about a 22-hour photoperiod. Secondly, these new types of dynamic lighting are more economical in terms of electricity consumption as they require even less photosynthetically active radiation for proper growth stimulation. With these advancements, breeders can opt for different approaches depending on their needs: fast SSD advancement when only a few seeds are available for the next generation, crossing blocks with improved flowering conditions, or phenotyping of traits requiring high biomass expression.

Nagamova et al. (2025) have also examined the influence of spectral quality. Their study revealed that wheat flowers earlier by around four days under speed breeding conditions

when exposed to low red: far-red ratios. This finding is important because although there is little or no improvement from one cycle to another given the inherently short ontogenetic periods, it adds up over many cycles. They further observed that reduced spike productivity can be mitigated, especially through monitoring crop nutrition. And this is precisely the kind of outcome that pushes ahead the discipline: it doesn't say that one specific spectrum is superior to the rest, but it points out that adjusting the spectral quality may help improve the overall technique.

Today, people are considering energy efficiency. The new protocols for fast breeding are transformational only if they can be maintained across all programs on a large scale of operation. The analysis of the 2023 modified system in wheat that exposed plants to natural sunlight supplemented with LED for a shorter period and used less electricity but still managed four generations per annum revealed an insight – it is possible to speed up breeding with low energy consumption even in those areas where this would be difficult because of the high prices, bad infrastructure, or unfavorable politics. To put it simply, contemporary trends in wheat speed breeding require accurate acceleration: the objective now is to decrease the biological cycle using an effective lighting environment that is reasonable from physiological, economic, and large-scale perspectives (Cha et al., 2023; Li et al., 2025).

Trait phenotyping and disease screening under accelerated conditions

The production of plants that are not well developed, but which grow fast indoors and seem to be at different stages of development when taken outside, has received a lot of criticism in speed breeding (Alahmad et al., 2018; Chhabra et al., 2024). However, this issue is being addressed in the new wheat trials. The first one was an important study done on durum wheat by Alahmad et al. (2018) that showed phenotyping of some quantitative traits even in one 77-day cycle from sowing to harvest under a speed-breeding environment. These were not just any traits either: they comprised root angle, root number, plant height, as well as diseases like crown rot and leaf rust, among others. The heritability was statistically highly significant, indicating that with the possibility of growing many generations in a year, one could subject them to repeated screening. To this day, this research is still applicable, as it revealed that speed breeding can help in obtaining certain information on the grown-up or almost grown-up phenotypes in addition to advancing lines (Alahmad et al., 2018).

Recent studies on Fusarium head blight (FHB) have reinforced the need to target phenotyping even as one speed up breeding. For instance, in their study, Chhabra et al. (2024) explored whether the conditions of speed breeding can effectively be used to evaluate the severity of FHB and

deoxynivalenol levels in wheat, and what they found is very interesting for breeders. It was discovered that most or at least some of the procedures for screening the disease gave comparable rankings under both natural and accelerated environments, with the difference that the rankings were obtained earlier in the selection and breeding cycle but still meaningful (Chhabra et al., 2024). This has great implications for any breeder. These kinds of diseases have a quantitative type of inheritance, whereby they are also very much affected by the environment; and apart from that, it costs a lot to phenotype them. Instead of using up resources on the field inoculation of some weak lines, it would be better if a program could identify such material at an early stage under controlled conditions and focus on inoculating, with the available resources, only the strongest genotypes.

Concurrent with this, the recent literature denies the truth of the generalization that “speed breeding works well for all phenotyping.” Transferability of phenotypic traits depends on what lies beneath, biologically speaking. Some phenotypic traits that may transfer well with the help of a good protocol include developmental timing, plant height, certain architectural features, and a few disease responses. However, there is still a need for field studies to determine general adaptability, end-use quality, resistance to target stresses, and complex genotype-by-environment interactions in relation to grain yield. Therefore, from what has been provided, it follows that transferability occurs selectively. This is because transferability occurs selectively, as proven by the available evidence. Speed breeding is at its best when the environment copies the biology behind the trait, or if the breeder is interested in getting rid of some plants at the beginning rather than arranging them in order at the end. To overcome this problem, modified systems that are user-friendly for breeders and maintain field-relevant variability rather than just increasing developmental compression are highly required. Speed breeding of wheat should therefore be approached with a trait-classification mindset. Traits can be grouped into those that can be screened directly indoors, those that can be screened indirectly or early, and those that must stay in the field. The third category remains unchanged, although many improvements have been made in the first two in recent years. Advances in the first two categories considerably strengthen wheat development pipelines by shortening generation times and the time needed to reach informative decisions (Alahmad et al., 2018; Chhabra et al., 2024). The trait classes that have already been shown to be useful under wheat speed breeding conditions are listed in Table 3.

Trait class	Representative evidence	Why it was informative	Breeding use	Main caution
Flowering time and plant height	Cha et al. (2023)	Heading date and culm length under modified SB correlated with field trends.	Early culling and parental characterization	Still requires local calibration by germplasm set
Root architecture traits	Alahmad et al. (2018)	Root angle and root number were measured in short cycles with useful heritability.	Selection for ideotypes and stress-related architecture	Pot size and substrate can alter absolute expression
Leaf rust/crown rot-related responses	Alahmad et al. (2018)	Disease-related phenotyping could be repeated several times per year	Rapid preselection for resistance sources	Indoor disease pressure must reflect causal biology
<i>Fusarium</i> head blight severity	Chhabra et al. (2024)	Accelerated rankings tracked normal-condition rankings well	Early triage before costly field or misting-house evaluation	Not a substitute for multi-environment confirmation
Bread-quality introgression effects	Cha et al. (2024)	Fast backcrossing plus markers enabled quality allele deployment	Rapid quality-gene transfer into elite backgrounds	Final end-use validation still depends on later-generation material
Early agronomic preselection after rapid inbreeding	Batista et al. (2024)	Large numbers of lines reached field-ready testing earlier	Shorter path from cross to yield trial	Speed does not replace replicated field evaluation

Table 3. Trait classes already shown to be useful under wheat speed-breeding conditions.

Integration with marker-assisted introgression and genomic selection

The effectiveness of speed breeding in wheat today lies in its potential to strengthen, rather than replace, modern breeding tools (Pandey et al., 2022; Ceran et al., 2024). Shortening the intervals between selection decisions makes marker-assisted selection, backcrossing, and genomic prediction more powerful. Cha et al. (2024) demonstrated this in wheat through introgression of the *Glu-B1i* high-molecular-weight glutenin allele. The team used a combined approach that included speed breeding, speed vernalization, phenotypic selection, backcrossing, and marker-assisted selection. They reported that near-isogenic materials were produced in less time while most of the recurrent parent genome was still recovered and bread quality was improved (Cha et al., 2024). The same reasoning applies in more complex genetic situations. Every extra generation in backcrossing adds to the time cost. By compressing generations through speed breeding while keeping selection accuracy with markers, the breeder benefits twice: the number of months spent is reduced, and so is phenotypic uncertainty. This is especially useful in introgression programs for disease resistance, quality, and adaptation in wheat varieties. Numerous recent articles on wheat support the view that speed breeding works best when combined with clear structural and molecular breeding objectives.

Genomic selection is also applied to polygenic traits. Watson et al. (2019) proposed that fast generation turnover through speed breeding can be combined with multivariate genomic selection, particularly when data on yield-related traits from

the accelerated environment are used to improve prediction. The idea behind this is very strong due to the fact that genomic selection quickens the selection process, just like what is provided by speed breeding in cross-pollinated cereals (Voss-Fels et al., 2019; Watson et al., 2019). It finds support from a simulation of FHB resistance in wheat conducted by Nannuru et al. (2025). More so, they indicated that in any genomic selection with speed breeding combination, all and any strategies lead to the greatest genetic gains. A slow phenotypic selection for this disease is seen to have a very interesting outcome as it relates to complex patterned inheritance of a trait that is hardly measurable in wheat itself (Nannuru et al., 2025).

The discussion has moved on from “Can speed breeding make wheat faster?” to “Which decisions become more powerful when cycle time is compressed?” in this research. Marker-based introgression, recurrent parent recovery, turnover of training populations for genomic prediction and early elimination of low-value lines are now identified answers to the question. It seems that speed breeding is most beneficial to wheat breeding programs that have invested in genotyping facilities, as it enhances the effectiveness of molecular decisions in such programs; every molecular decision becomes more effective when you get rid of isolation periods of about 4 – 5 months between generations (Watson et al., 2019; Cha et al., 2024). The integration of speed breeding with these tools is shown in Figure 3, and the combinations with other wheat improvement technologies are summarized in Table 4.

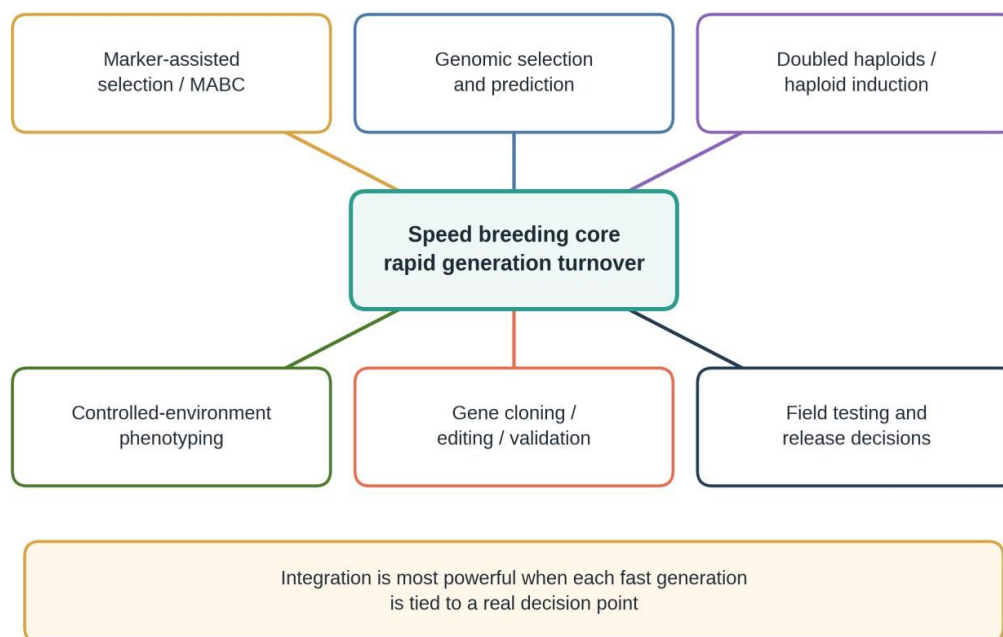


Figure 3. Integration of speed breeding with molecular and quantitative breeding tools. MABC, marker-assisted backcrossing.

Paired technology	Representative wheat example	Main benefit of pairing	Current maturity in practice
Marker-assisted selection/backcrossing	Cha et al. (2024)	Faster movement of target alleles and quicker recurrent- parent recovery	High: already practical where markers are available
Genomic selection	Watson et al. (2019); Nannuru et al. (2025)	More selection cycles per unit time and faster use of genomic breeding values	High conceptually; implementation depends on the genotyping workflow.
Speed vernalization	Cha et al. (2022)	Makes winter germplasm compatible with accelerated pipelines	High-maintenance enabling tool for winter wheat
High-throughput vernalization	Dhakai et al. (2025)	Better scalability and broader fit to strong winter types	Emerging but highly practical
Doubled haploids/haploid induction	Discussed in recent reviews such as Blinkov et al. (2025)	Alternative route to fixation; complements rather than replaces SB	Moderate: valuable but genotype- and infrastructure- dependent
Rapid disease-gene cloning	Wang et al. (2025)	Shortens the discovery-to-deployment interval for resistance alleles	Emerging frontier with very high strategic value
Digital phenomics	Future-oriented integration noted by Kabade et al. (2025)	Turns controlled environments into data-rich decision spaces	Emerging; likely to expand strongly

Table 4. Combination of speed breeding with other wheat-improvement technologies.

Line fixation, haploid systems, and accelerated gene discovery

Becoming homozygous quickly, or understanding genes quickly, in wheat is not just about moving through selfed generations faster; it also involves reducing the distance to homozygosity and improving understanding at the gene level (Blinkov et al., 2025; Wang et al., 2025). In this respect, doubled haploid (DH) production and haploid induction remain supportive of speed breeding and are not alternatives

to it. Speed breeding can move segregating populations through SSD quickly, while DH can deliver complete homozygosity instantly. However, recent reviews indicate that line development through DH on average still takes a lot of time and depends on genotype; speed breeding therefore plays an important role wherever DH capacity is weak, costly, or not uniformly effective across germplasm. The best modern perspective is thus a combined plan: use DH where the value of fixation justifies the high cost, and use speed

breeding for cheap, quick progress across large populations (Pandey et al., 2022; Blinkov et al., 2025). The two methods still remain separate entities as of now and will require a considerable period of time to be absorbed into routine wheat breeding, even with the likelihood of convergence due to the emerging *in vivo* haploid induction systems in wheat.

Cloning of resistance genes is another piece of evidence that shows how much speed breeding is being utilized nowadays. For instance, Wang et al. (2025) provided a 6-month framework for cloning resistance genes in wheat through an enhanced mutagenesis, speed breeding, and bioinformatics platform. By shortening the generation interval, they demonstrated the feasibility of a rapid *Sr6* cloning project that took only 179 days, a pace that conventional discovery pipelines could not have matched (Wang et al., 2025). This is important for breeding because cloned genes help to improve marker design, trait deployment, allele stacking, and knowledge-based resistance management.

Such work has both technical and conceptual significance. In the past, breeders complained that new lines took too long to develop because of the gap between basic genetic discovery and the pace of line development. Speed breeding approaches have reduced this gap. Validation and tracking of a gene, as well as introduction and pyramiding, can take less time when fewer biological stages separate consecutive decisions. This is also why edited or mutant alleles can be validated functionally, mapping populations produced quickly, and materials recycled into pre-breeding at high rates. Consequently, these recent developments show that speed breeding is evolving into another link in the chain from gene discovery to cultivar development, rather than being just an isolated cultivation art (Wang et al., 2025; Ceran et al., 2024). In wheat, for disease resistance, end-use quality, and abiotic adaptation, all of which require accurate allele management, this may turn out to be one of the technologies that leave a lasting legacy and prove difficult to surpass.

Implications for breeding-program design and annual genetic gain

Speed breeding cannot be evaluated solely by the number of days it removes from the time to flowering. Instead, it should be assessed by its effect on annual genetic progress. According to the breeder's equation, genetic gain per unit of time improves as the generation interval decreases, provided that selection intensity and accuracy remain high (Bhatta et al., 2021; Watson et al., 2019). For this reason, some of the most important recent articles focus not only on plant growth but also on workflows. They assess the rate at which a breeding population can be advanced for decision-making. This matters because, within a year or a multi-year selection pipeline, the chances of selecting the best individuals differ depending on whether the system is a 54-day cycle in spring

wheat, a four-generation modified glasshouse system, a five-generation winter platform, or a 22-day reduction in winter cycle length (Batista et al., 2024; Cha et al., 2022; Cha et al., 2023; Dhakal et al., 2025).

From this perspective, breeders should now design plans that focus more on decision nodes than on environments. For example, crossing blocks, F2 and F3 advancement, early-generation disease screens, marker-based backcrossing, and training-population renewal for genomic selection each require different environments. The greatest benefit of speed breeding lies in its use at specific developmental stages where time is critical. This means that evaluation of factors like genotype-environment interaction, yield stability, and farmer-related performance, which cannot be evaluated in a controlled environment alone, should reserve some space and testing in a natural environment. Therefore, when duties are divided between artificial and natural environments like this, speed breeding ceases to be just another acceleration technique and starts to serve its purpose better—enhancing the overall program.

Speed breeding affects the economics of population structure, which is another important design flaw. The fact that many generations may elapse before a line undergoes replicated testing allows breeders to maintain broad recombination in the initial stages and delay strong selection as fixation improves. Recurrent improvement programs, on the other hand, may shorten the selection cycle and cross superior material again at high frequency. This is because speed breeding cycles reduce the time cost of recovering the recurrent parent in marker-assisted backcrossing. In genomic selection, rapid turnover enables earlier action on breeding values and more frequent updating of training populations. Speed breeding is therefore more than a time saver; it makes certain breeding architectures feasible (Watson et al., 2019; Nannuru et al., 2025; Cha et al., 2024).

Nevertheless, some of the literature calls for moderation. System speed does not necessarily equal program quality. Annual gain may not be higher with faster cycling if the protocol reduces seed set, requires more facilities than the program can afford, or improves the reliability of indoor phenotyping at the expense of outdoor phenotyping. Hence, the suitable goal for efficient cycle compression would be effective acceleration of annual gain that does not affect fertility, which means having reasonable capacity and making sound decisions too. More and more studies on wheat appear to confirm this view, which can be seen as a sign that the field is maturing (Cha et al., 2023; Ceran et al., 2024).

Constraints, trade-offs, and unresolved challenges

Despite considerable improvement, speed breeding in wheat still has some limitations and costs (Wanga et al., 2021; Ceran et al., 2024). The first is biological fidelity. A plant grown

under long photoperiod, restricted rooting volume, and crowded indoor spacing is different from one grown in the intended crop production environment. This difference may be tolerable, or even advantageous, for traits that are closely related to developmental time or have a simple structure. Nonetheless, controlled conditions provide only a limited screening opportunity for grain yield, adaptation under terminal stress, lodging at field fertility levels, and complex source-sink interactions. The risk is not that indoor screening is useless, but that breeders may assume an indoor phenotype is more relevant to the field than the biology of the trait indicates.

Winter wheat has benefited greatly from fast vernalization techniques and high vernalization throughput, but there is still a strong genotype-by-protocol interaction. Some materials can satisfy their vernalization needs quickly under warm conditions with long days, whereas others respond poorly and must be handled very carefully. Even in spring wheat, flowering response, fertility, seed dormancy, and tolerance of high-density single-seed descent may differ. In other words, local calibration is important in a breeding program, since one germplasm set may not follow a protocol validated on another (Ficht et al., 2023; Dhakal et al., 2025).

Operational challenges come third. Energy use for lighting equipment and heat regulation, labor for planting and harvesting, and fast seed drying for replanting all place limits on how far a system can be scaled. These limitations were not

considered during the early stages of implementing speed breeding because it was tested under strictly controlled conditions in research facilities. Nevertheless, the emerging literature is now quite realistic (Cha et al., 2023; Li et al., 2025). Modified systems that save energy, dynamic lighting recipes, as well as pot size, substrate, and fertilizer agronomic optimization have been seen in this field. Thus, acceleration should be cheap and easily reproducible in addition to being biologically possible. Some programs may require hybrid systems where the primary source is natural sunlight while artificial light serves as a backup at specific times of the day or year; this is more likely if they work in locations with high electricity costs and unreliable power supply.

Seed quality and physiological stress are also not fully resolved. The cycle can be shortened through early harvest, provided the seeds are mature enough and germinate as expected. Very dense stands may allow high throughput, but they may also reduce the number of seeds per spike or increase non-uniformity. Similarly, manipulating the light spectrum with a low red:far-red ratio speeds up flowering, but sometimes hampers spike productivity and shape. The challenge going forward is to quantify these trade-offs so that breeding becomes a matter of informed choice between fast, faster, and fastest options for different generation goals (Li et al., 2025; Nagamova et al., 2025). The main constraints and practical mitigation strategies are summarized in Table 5.

Constraint	Why it matters	Practical mitigation	Priority level
High electricity demand	Can make long-day systems expensive at scale	Use sunlight-assisted systems, efficient LEDs, dynamic light schedules, and task-specific recipes.	High
Variable response of winter germplasm	A single vernalization protocol may not satisfy all lines	Pre-classify germplasm; use speed vernalization or HTV options; validate locally	High
Poor translation of some traits to field conditions	Fast plants are not always selection-relevant plants	Classify traits into indoor-direct, indoor-indirect, and field-only categories	High
Crowding stress in SSD	High density can reduce seed set and uniformity.	Tune pot size, substrate, nutrition, and irrigation around the target density	Medium
Immature seed or dormancy problems	Early harvest saves time only if the seed remains viable	Use validated harvest windows, drying protocols, and germination management	Medium
Workflow bottlenecks after harvest	Calendar gain is lost if threshing, genotyping, or re-sowing is slow	Plan seed handling, sampling, and data capture as an integrated production line	High
Limited facility capacity	Small facilities may not handle whole-program demand	Target the true breeding bottlenecks rather than trying to move every generation indoors	High

Table 5. Operational constraints in wheat speed breeding and practical mitigation strategies.

Practical implementation framework for wheat breeders

One can efficiently utilize the recent literature through purpose-specific deployment (Pandey et al., 2022; Cha et al., 2023). When crossing blocks, it is important to have synchronized flowering, high pollen viability, and plants that are strong enough to endure many pollinations. At this point,

it would be better to use a lighting program that is reproductively reliable and mildly aggressive than the fastest one available because reproductive reliability is more important than absolute cycle compression. The breeder demands rapid flowering, easy seed production, and reasonable throughput in the early segregating generations of

single seed descent. As a result, one should give priority to dense planting, small pot sizes, and quick post-harvest operations rather than trying to increase the number of seeds per plant. In case of marker-assisted backcrossing or recurrent parent recovery, the protocol must emphasize short generation span and taking clean tissue for genotyping while confirming traits at latter generations. The system should comply with trait biology for disease screening or quality preselection and be applied only if the trait's expression is significant in a controlled environment.

A few practical rules emanate from this very focused perspective. Firstly, speed breeding protocols must be validated in wheat programs before they are scaled up, using a representative cross-section of germplasm. It is not appropriate to mix spring, facultative, and winter materials under the default system without making changes. Secondly, for every rapid cycle, the program should indicate the decision to be taken. The cost of maximum acceleration may be unjustifiable if the decision-making process is unrelated to any critical choice. Thirdly, infrastructure planning should focus on bottlenecks rather than total population size (Batista et al., 2024; Cha et al., 2023). Even a modest-capacity facility can make a difference in a breeding program if it is employed at points where seasonal delays occur and slow down progress significantly. Lastly, breeders must always use

certain anchor characteristics like heading date, height, fertility, disease response, and seed quality to compare accelerated samples with those grown under natural conditions. By doing this, any divergence between the assumed conditions of the controlled environment and actual field conditions will be avoided.

Managerial issues can also make speed breeding ineffective in the physiological sense. The best results are obtained only if speed breeding is planned well using calendars. Seed harvest, drying, threshing, data capture, genotyping, and re-sowing should be coordinated so that no biological acceleration is wasted through slow administration. Many recent studies argue the same thing implicitly: the advantage offered by a 54-day cycle or a shortened winter vernalization period is useful only if the breeding program can move seeds quickly and make fast decisions (Batista et al., 2024; Dhakal et al., 2025). Rapid wheat development thus requires an environmental protocol coupled with workflow engineering. Speed breeding will be most valuable in breeding programs that treat it as part of a larger controlled production environment rather than as just another glasshouse-based technology. Figure 4 presents a decision framework for matching a speed breeding pathway to breeding objectives, and Table 6 gives a purpose-specific deployment guide.

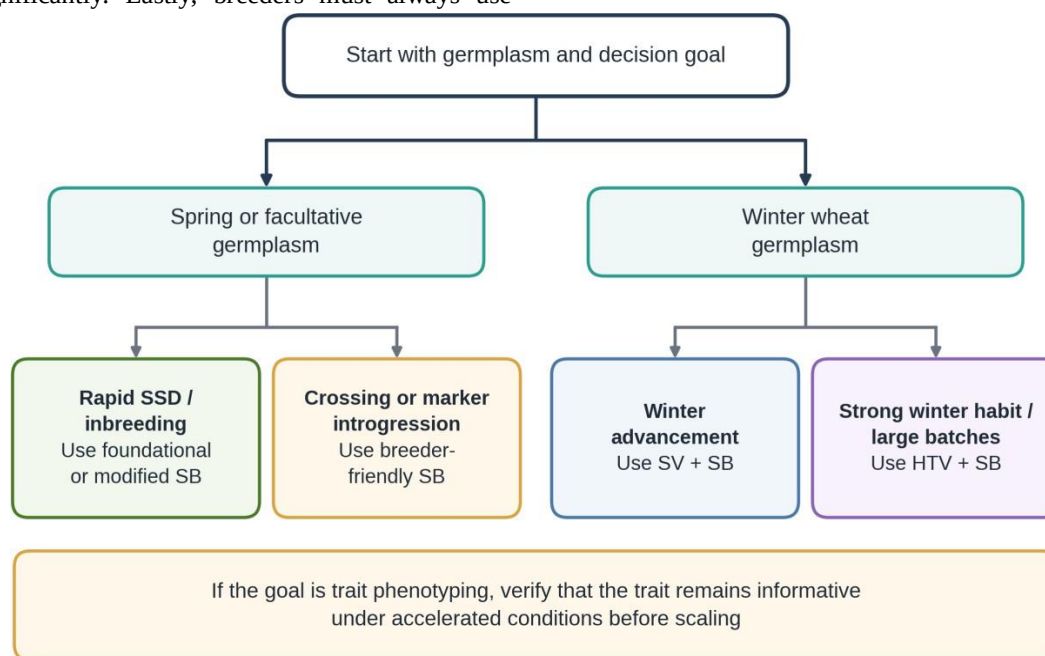


Figure 4. Decision framework for matching a speed-breeding pathway to wheat breeding objectives. SB, speed breeding; SSD, single-seed descent; SV, speed vernalization; HTV, high-throughput vernalization.

Breeding stage or objective	Primary priority	Recommended accelerated pathway	Key caution
Crossing block management	Synchronized flowering and fertile spikes	Breeder-friendly SB or moderate indoor recipe	Do not sacrifice floral reliability for maximum speed
Spring-wheat SSD advancement	Fast generation turnover	Foundational or modified SB	Maintain enough seed set for smooth re-sowing
Winter-wheat advancement	Completion of vernalization plus rapid flowering	SV + SB or HTV + SB	Strong winter types still need calibration
Marker-assisted introgression	Short cycle interval plus genotyping	SB integrated with backcrossing and marker selection	Trait validation should follow in later generations
Controlled-environment disease preselection	Early discard of clearly susceptible material	Trait-specific SB phenotyping workflow	Use only where biological relevance has been verified
Rapid gene validation/cloning pipeline	Fast turnover of mutants or segregants	SB linked with genomics and targeted screening	Discovery speed must still be matched by confirmatory evidence
Transition to field testing	Reliable plot-level comparison	Shift fixed or near-fixed material from SB to field trials	Yield and adaptation remain field-anchored

Table 6. Purpose-specific deployment guide for wheat speed breeding.

Future directions for speed breeding 3.0 in wheat

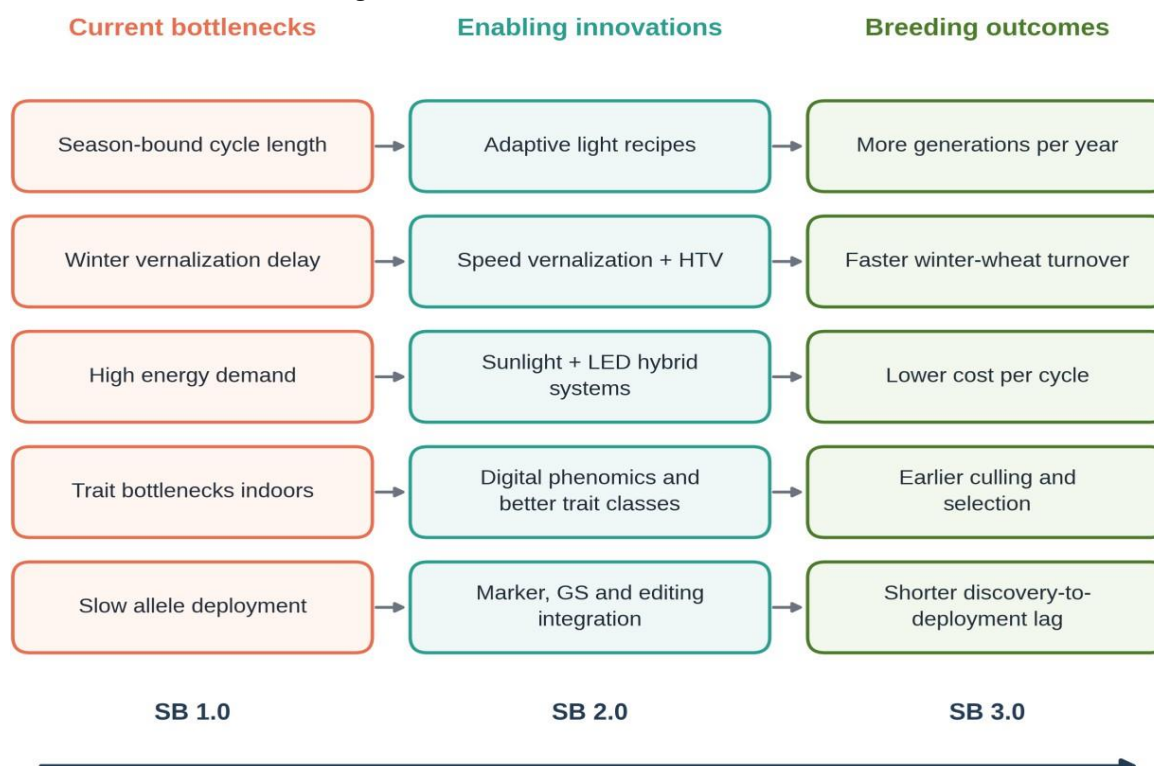
The next phase of speed breeding in wheat will most likely be characterized by adaptive control rather than by longer photoperiods (Kabade et al., 2025; Li et al., 2025). The “speed breeding 3.0” paradigm, as described in some recent articles, refers to adjusting the lighting period and quality, temperature, and chemical and physiological factors according to the type of germplasm and the breeding aim. This means that there will be different protocols for wheat, for example, two protocols for spring SSD advancement and phenotyping, one for winter crossing in SSD and vernalization-sensitive materials, and another for integrating edited or marker-selected alleles into elite backgrounds. The ability to shift from one recipe to another within the same pipeline will most likely define the most effective systems. A roadmap toward speed breeding 3.0 is shown in Figure 5. Digital phenomics will increase the worth of speed breeding. Instruments are much easier to install in controlled environments than in field plots, which is why such environments are preferred for monitoring development through images, leaf traits, and canopy and disease progression. With advances in machine vision in controlled environments, there will be not only a space for rapid generation turnover but also a standardized arena for early trait prediction. Combined with genomic selection, this may make every indoor generation more valuable than it is on its own (Watson et al., 2019; Nannuru et al., 2025). Breeders will be able to move from one generation to the next more

effectively, with better data on which plants or families to prioritize.

In the future, gene editing and allele deployment will be connected more closely with other technologies. The breeding value of a favorable edit depends on how quickly it can be validated, fixed, pyramided, and tested after it is made. Speed breeding shortens each of these processes, and the same applies to cloned resistance genes and diagnostic markers. With the growing pace of wheat pan-genomics and functional gene discovery, breeders will need biological pipelines that move information into practical germplasm at an equally high speed. Speed breeding is among the few technologies that can directly bridge this gap (Wang et al., 2025; Ceran et al., 2024).

Democratization also matters a lot. Initially, many publications came from highly equipped research teams, but more recent ones advocate energy-efficient, breeder-friendly systems that use sunlight. This will not be achieved by implementing an extremely fast speed breeding protocol that is unattainable for most wheat programs. If speed breeding remains confined to a few specialized centers, its promised technical impact on the improvement of global wheat germplasm will remain largely unrealized. If, on the other hand, it is introduced as a low-cost, adaptable, and modular technology for accelerating genetic gain, it could affect varietal development across different environments and institutional settings (Cha et al., 2023; Kabade et al., 2025).

Figure 5. Roadmap toward wheat speed breeding 3.0. SB, speed breeding; HTV, high-throughput vernalization; GS, genomic selection.



Conclusion

In the past, speed breeding in wheat was accelerated using simple long-day approaches. However, this has changed due to some recent developments which have made it possible for there to be better systems of accommodating winter habit that are also energy efficient, consume low amounts of modified light quality that also support specific phenotyping tasks and easily integrate with molecular markers, genomic prediction, backcrossing and gene discovery. The literature indicates that accelerating growth rates in wheat is no longer all that matters, although this aspect still counts; one can now go faster but keep well within the time for making decisions by breeders as well as the general program logistics.

Speed breeding helps with inbreeding and advancing large populations of spring wheat during the off-season. Speed vernalization for winter wheat and high-throughput vernalization have removed one of the greatest obstacles to fast-track breeding (Cha et al., 2022; Dhakal et al., 2025). In integrated breeding, the technology increases the effectiveness of marker-assisted selection, genomic prediction, and rapid gene cloning, because it reduces the time lags between consecutive decisions and their biological implementation. Nevertheless, these recent studies exercise reasonable caution. They still require field validation and genotype-specific adjustments, and they suggest that, in the most advanced systems, it is better to prioritize speed only as far as it stays in line with phenotype-related considerations and is practically feasible.

To sum up, a clear conclusion can be drawn from the literature reviewed. Rapid wheat development through speed breeding is currently an enabling technology whose maximum impact is felt when it is used selectively, with full knowledge of the breeding program. There will be no one-size-fits-all solution to speed breeding for wheat improvement. Adaptable approaches that use empirical data to select the most appropriate method for propagating plant material, desired characteristics, and breeding objectives will also be relevant (Pandey et al., 2022; Kabade et al., 2025).

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