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**Review Paper**

# Breeding for ideotype in field crops: optimizing yield, resource allocation and adaptability in cereals and legumes

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ABSTRACT

**Breeding for ideotype in field crops plays a crucial role in optimizing yield potential and resource allocation. While self-pollinated cereals have achieved significant yield improvements through enhanced input responsiveness, grain legumes have lagged in comparable genetic advancements. Cereals exhibit greater receptivity to increased inputs, such as nitrogen fertilization, leading to enhanced cultivar performance. Grain legumes, however, remain an essential dietary component, providing micronutrients often lacking in modern cereal varieties. Breeding efforts across diverse agro-ecological conditions aim to enhance yield potential, improve quality traits, and minimize post-harvest losses. Key constraints, such as plant lodging and pod dehiscence, are critical in both cereals and legumes, with pod distribution being a unique challenge in legumes. Advances in breeding have led to improved adaptability, higher resistance to biotic and abiotic stresses, and cultivars with better operational ease. The selection of an optimal breeding strategy depends on the target environment, trait inheritance patterns, and cultivation conditions, ensuring sustainable crop improvement.**

**Key words:** Breeding, cereals, legumes, ideotype resource allocation, stress resistance yield improvement

Plant breeding programmes across globe aim to improve the yielding adaptability, stable performance, uniformity in expression of traits, biotic and abiotic stress resilience and good harvest quality. Breeding agricultural crops for raising varieties with best integration of traits ensuring its adaptation to varying climatic conditions in addition to the higher yields precisely defines ideotype breeding. Identification of target traits suitable for selection and expressing a desired phenotypic expression for each of them is the basic prerequisite in ideotype breeding. Unravelling genetic diversity for the particular traits responsible directly or indirectly for grain yield as incorporation of genetic diversity for yield traits is a pivotal move towards ensuring food security in present as well as future. Ideotype breeding provides a way of bridging the gap between the utilization of unimproved germplasm (wild species and their relatives) with improved crop gene pool (Rasmusson, 1987). Crossing of desired parents with quantifiable and requisite attributes is the basic step in classical plant breeding. As the breeding objectives differ depending on the prevailing conditions, it might not be suited to rapid improvements in overall cropping conditions or foster diversity of customer demand. The ideotype breeding encourages hastening selection of breakthrough varieties with desired plant model aspirations with distinct trait advantage with the existing varieties. A new plant type's ideotype is developed by a creative process that involves developing a conceptual representation and a set of predetermined tactics. In order to lower production costs and address the issue of the labour scarcity experienced in the main field crop growing niches, the development of cultivars in the majority of field crops that are better appropriate for mechanized harvesting is currently a primary breeding priority. Plant lodging and pod breaking, which are significant harvest issues for cereals and pulses, respectively, are also significant harvest challenges for legumes, which are botanically considerably different from cereal spikes in terms of the position and distribution of their pods on the stem. In the majority of places where pulses are grown, increasing heat and drought resistance has a large potential to increase pulse yields (Porch *et al*., 2013). However, the scarcity of stress resistance genes hinders breeding efforts to develop pulse crops that can withstand biotic and abiotic challenges. At the same time identifying new varieties with machine ready attributes ensuring ease of cultivation and harvesting operations is essential under current scenario for maximized returns. According to Kelly *et al*. (1998), ideotype breeding has been successful in creating a variety of bean varieties, including navy, pinto, and great northern beans, with better architectural characteristics and a high potential for seed yield. However, depending on the type of seed or the intended setting for cultivation, the ideotype behaviour may change. Various ideotypes may also be used in cultivar development programs depending on the plant breeder's assessment and the state of the breeding environment. A significant breeding problem is the conversion of pulse crops generally to a fully mechanized crop. In order to accomplish this research goal, we must combine a number of growth characteristics, such as a determinate growth habit, more upright plants with a compact (bush-type) canopy, preferably low unit seed weight, shorter internodes and short secondary branches, lodging resistance, and even branches with pods that are above the plant canopy. Common beans have undergone extensive plant breeding, resulting in a variety of cultivars with a wide range of morphological and agronomic characteristics, including variations in seed size and colour as well as growth habit (Singh *et al*., 1991). Determinate growth, which is linked to decreased branching, shorter and fewer internodes, decreased twining, insensitivity to day length, and most crucially, an increased allocation of biomass to reproductive growth, is one of the most frequently favored features (Singh and Schwartz, 2010). Certain agronomic conditions also favor the use of varieties with a determinate growth habit: they are better adapted to shorter crop growing seasons because they mature earlier; they produce pods over a shorter and more consistent period of time, simplifying the harvest of green beans; and they are more amenable to mechanized cultivation and harvest (Kwak *et al*., 2012). An ideal ideotypes framework is depicted in (Fig. 1).

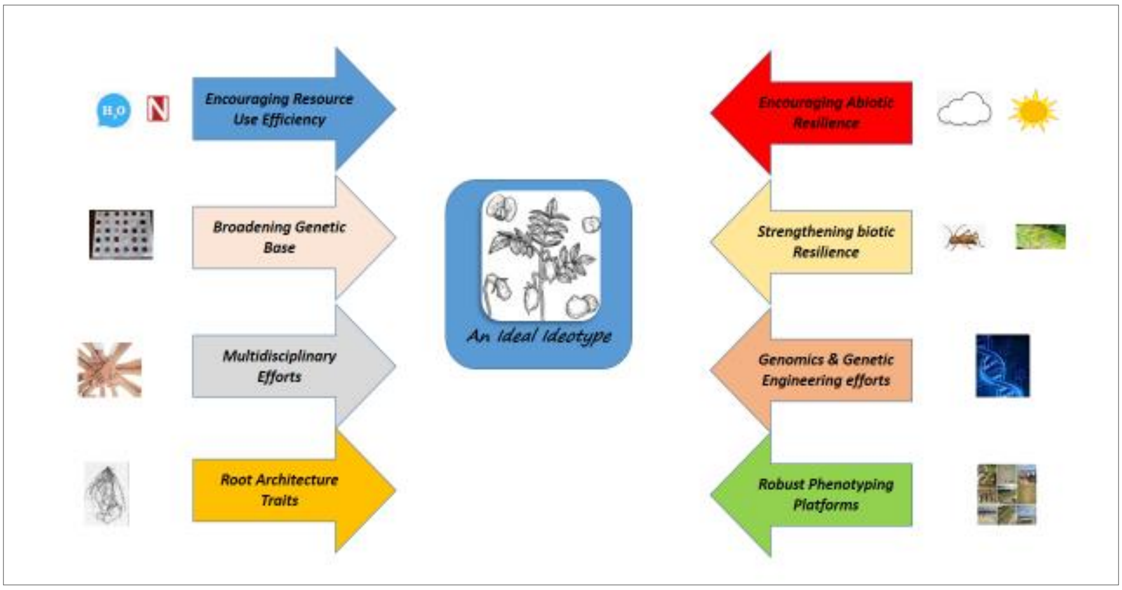


**Fig.1: A model framework to develop an ideal ideotype of yield and climate smart attributes**

Many breeders have embraced the method of selecting individuals with erect plant architecture in the majority of crop breeding programs to promote high grain output (Vanesa *et al.*, 2013). This plant's architecture makes it simple to utilize cultural practices, allows for cheaper mechanical harvesting, and assures that pods may avoid coming into touch with the ground dirt, resulting in higher-quality seeds. This plant architecture reduces the prevalence of various illnesses, such as white mold (Pires *et al.*, 2014). In addition to erect plant architecture, selection must emphasize commercial grains and high grain yield. These characteristics are uncommon in single parents but can be induced through the use of effective breeding techniques. The best breeding approach to include all auxiliary features in a single enhanced line is hybridization.Therefore, choosing parents who complement each other well is a requirement. In common bean breeding, the main goals are to increase production, quality, environmental adaptation, and profitability (Singh and Singh, 2015). However, bush type cultivars for food processing must have higher yield and freeze-ready pod qualities in response to market needs of the frozen vegetable industry. Pods for frozen processing must, under some circumstances, be a dark green hue, straight and stringless, with a diameter of 7 to 9 mm and a high sugar content. The ideas for creating an ideal ideotype model are based on the morphological and reproductive trait characteristics linked to effective sunlight capture for photosynthesis and translocation of the photosynthesizing pigments in the grains/products. One of the main cereal crops, rice serves as a model for ideotype research since it may be genetically modified. Yang and Hwa (2008) provided a compelling explanation for plant architecture and variety improvement by arguing that plant architecture is strictly governed by genetics and that net grain output in cereal crops is influenced by a range of agronomic factors. The recent advances in our understanding of the fundamental patterning mechanisms that control the pattern of rice plant tillers, the structure of its stems, and the pattern of its leaves. Similar to this, various authors proposed the dwarf rice ideotype, which includes the most productive tillers, the shortest stem height, the largest culm diameter, the slowest internode elongation, and the shortest erect leaves with the medium-widest leaflets, the greatest number of panicles, and the highest harvest index. Plant physiologists' focus on the identification of basic morphological qualities that have some bearing on physiological processes affecting the yield of the economic organs was brought about by the pursuit of the ideotype idea. (Thurling, 1991).

**Features of crop ideotypes:** An ideal ideotype comprises set of desired traits responsible for maximising crop returns over the reference crop in terms of morphological superiority or physiological efficiency in specified cultivation scenarios. Ideal plant types or model plants in various economically important crops are as under (Table 1).

**Ideotype for specific situations:** The original Donald ideotype was designed for low- or no-stress conditions where plant light capture was the primary bottleneck for productivity increases. Donald focused on selecting locally adaptable dwarf wheat genotypes with strong culms, a limited number of erect leaves, low tillering capacity, large erect awned ears, high disease resistance, and low plant competitive ability in a crop sown at high density as essential target traits to realize high yield under ideal circumstances. In the context of the various competitive contexts in which cultivated plants, and notably grains, are grown, Donald and Hamblin (1976) developed the idea of the ideotype. With particular relevance to cereals, they proposed the concepts of exclusion, rivalry, and crop or community ideotypes (Table 2). A single feature cannot possibly enhance plant performance in all growing situations, claims Tardieu (2012). For example, the ideotype recommended for non-stress situations would not function well in water-limited environments because under such stressful conditions crop growth and development is affected to varying degrees depending on the timing, severity, and duration of stress events, the interactions between water deficit and other factors such as temperature and nutrient availability. Consequently, it was suggested that certain ideotypes should be created for intended contexts.

**Table 1: Ideal plant types or model plants in various economically important crops**

| Rice | Wheat |
|---|---|
| ✓ Semi dwarf plant stature<br>✓ Robust tillering ability<br>✓ Strong short erect and wide angled leaves.<br>✓ High grain number per panicle.<br>✓ Heavy panicles and high panicle number per unit area. Drooping panicles at maturity.<br>✓ High harvest index. | ✓ Strong and dwarf stem<br>✓ Erect and few small leaves.<br>✓ Big ear size with erect posture<br>✓ Moderate tillering (9-10), erect and compact head with erect leaved canopy<br>✓ Presence of awns on the grains.<br>✓ Pubescence present on whole plant to prevent aphid<br>✓ Single culm. |
| **Maize** | **Cotton** |
| ✓ Efficient translocation of photysynthates.<br>✓ Short Anthesis silking interval.<br>✓ Smaller tassel size.<br>✓ Stiff-vertically-oriented leaves above the ear.<br>✓ Photoperiod insensitivity.<br>✓ Cold tolerance for early sowing.<br>✓ Long Grain -filling period.<br>✓ Ear-shoot prolificacy.<br>✓ High shelling percentage (>85%)<br>✓ Slow leaf senescence | ✓ Short compact plant stature (90-120 cm).<br>✓ Determinate fruiting habit with unimodal bolling distribution.<br>✓ Early maturity (150-165 days).<br>✓ High fertilizer responsiveness.<br>✓ Resilience to insect pests and diseases.<br>✓ High physiological efficiency.<br>✓ High degree of inter-plant competitive ability.<br>✓ Early maturity (150-165 days).<br>✓ Few, small and thicker leaves.<br>✓ Gossypol free cotton seed<br>✓ Sparse hairiness.<br>✓ Medium to big boll size with synchronous bolling.<br>✓ Nutrient responsiveness<br>✓ Resistance to insects and diseases. |
| **Beans** | **Chickpea** |
| ✓ Narrow upright plant stature (50-55cm height).<br>✓ Small to medium seed size.<br>✓ Indeterminate flowering habit.<br>✓ Dominant main stem, upright, thick, hypocotyl.<br>✓ Pod distribution on higher nodes, through upper part of canopy.<br>✓ Basal acutely angled branches (2-3) in number.<br>✓ Biotic and abiotic resilience. | ✓ Imparipinnate-leaves<br>✓ Double/multi-podded pods.<br>✓ Extra-large-seeded pods with 50–60 g per 100-seed weight.<br>✓ Combine ready plant stature with plant height of 58–62 cm.<br>✓ Heat tolerance.<br>✓ Disease resistance to major diseases. |
| **Barley** | **Pea** |
| ✓ Short plant stature.<br>✓ Long awns on grains.<br>✓ High harvest index.<br>✓ High biomass.<br>✓ High Kernel weight and kernel number. | ✓ Abiotic stress resilience including cold & heat tolerance.<br>✓ Root flooding sensitivity.<br>✓ High Plant stature.<br>✓ Early flowering and maturity<br>✓ High pod number<br>✓ Indeterminate growth habit<br>✓ Presence of leaf cuticular wax |

Performance stability was promoted as a crucial varietal trait by Braun *et al*. (1992) for locations with high inter-annual weather fluctuation. Ceccarelli (1989) asserts that another approach to crop development is to select for more exact adaptation. Various Ideotype kinds have been categorized based on the population and the environment in which they are developing.

**Table 2: Characteristics of isolation, competition and crop or communal ideotype**

| Characteristics | Isolation ideotype | Competition ideotype | Crop/ communal ideotype |
|---|---|---|---|
| Ecosystem | The plant grown in isolation | The plant grown in a mixed community | The plant grown in dense monoculture |
| Cereal community | Widely spaced plants or rows | Segregating populations or varietal mixture at crop density | crop |
| Yield criterion | Weight of grain per plant | Weight of grain per plant | Weight of grain per hectare |
| Competitive ability | Of no significance | Strong competitive ability required | Weak competitive ability; minimum mutual interference among like plants |
| Habit | Lax or prostrate habit, permitting leaf cover over a maximum area | Taller than neighbours, especially during early growth stages | Erect for minimum interference; dwarfness for mechanical strength and improved HI |
| Canopy | Extensive leaf display for maximum light interference | Extensive display to shade neighbours, especially during early growth | Minimum leaf display, sufficient only to form adequate ear. Minimum interference with foliage |
| Leaves | Many long, wide, thin, horizontally displayed | Many long, wide, thin, horizontally displayed | Few small, erect leaves to give favourable light profile and a higher HI |
| Root system | Rapid and sustained growth of roots to permit water and nutrient uptake adequate for maximum growth | Early rapid growth of roots exceeding that of neighbours, penetrating particularly into soil layers likely to be critical in competition for water and nutrients | Adequate to ensure sufficient exploitation of the soil environment by the whole community of roots by the end of the season |
| Tillering | Free-tillering | Free-tillering | Sparse or no tillering |
| Culm survival | High survival | Enough to exploit the residual environment | Full survival |
| Ear size | Large ears | Large ears | Ear size, grains per ear, Many florets per unit of biomass and per unit area. |
| Grain number per ear | Many grains per ear | Many grains per ear | |
| Grain size | Large grains | Large grains | High grain weight per unit of biomass (HI) and per unit area when at optimum density |

*Source: (Donald and Hamblin, 1976)*

**Isolation ideotype:** Wide crop spacing guarantees the best possible flourishing of these ideotypes and achieves the highest possible production levels. When a cultivar is established, it is the biological model that is anticipated to provide a larger amount or quality of grain, oil, or other useful product. In most cereals, an isolation ideotype is thought to be a lax, free tillering genotype with spreading leaf plant that would be able to explore the surroundings as thoroughly as possible.

**Competition ideotype:** In most instances, a genetically heterogeneous population (segregating populations of crosses) benefits greatly from the competition ideotype. Crops with homogeneous individuals, such as pure lines, typically have a low harvest index because a higher investment of dry matter in plant structure usually comes at the expense of seed. A tall, green, free-tillering plant that may shadow its less aggressive neighbors and fiercely compete for nutrients and water is classified as a competition ideotype in the case of cereals.

**Crop/ communal ideotype:** These ideotypes display higher harvest indices and little resource demand per unit of dry matter production. When surrounded by other plants of the same morphology, which creates a highly competitive environment, erect, sparsely tillering plants with small erect leaves would fare better; nonetheless, they would be less successful. Its performance would also be effected in an isolation environment. Weak competitor is the key characteristic of this type of crop ideotype in widely spaced crops, a breeder tends to rate plants partly for the isolation environment where generally lax, free-tillering, leafy plants would perform excellent. The selection would be of a different kind in close-planted segregating populations providing a competition environment where tall, long leaved plants will succeed. In all segregating populations, the contrast from the crop environment is further aggravated by heterozygosity and hybrid vigor, variations in the physical environment from plant to plant and the inability to replicate in space and time (Shebeski, 1967). In the belief that they will succeed in the crop or community setting, plant breeders typically choose their candidates from habitats of isolation and competition.

**Designing an ideal ideotype:** Ideotype designing in any agronomically economic crop is basically spit into following steps:

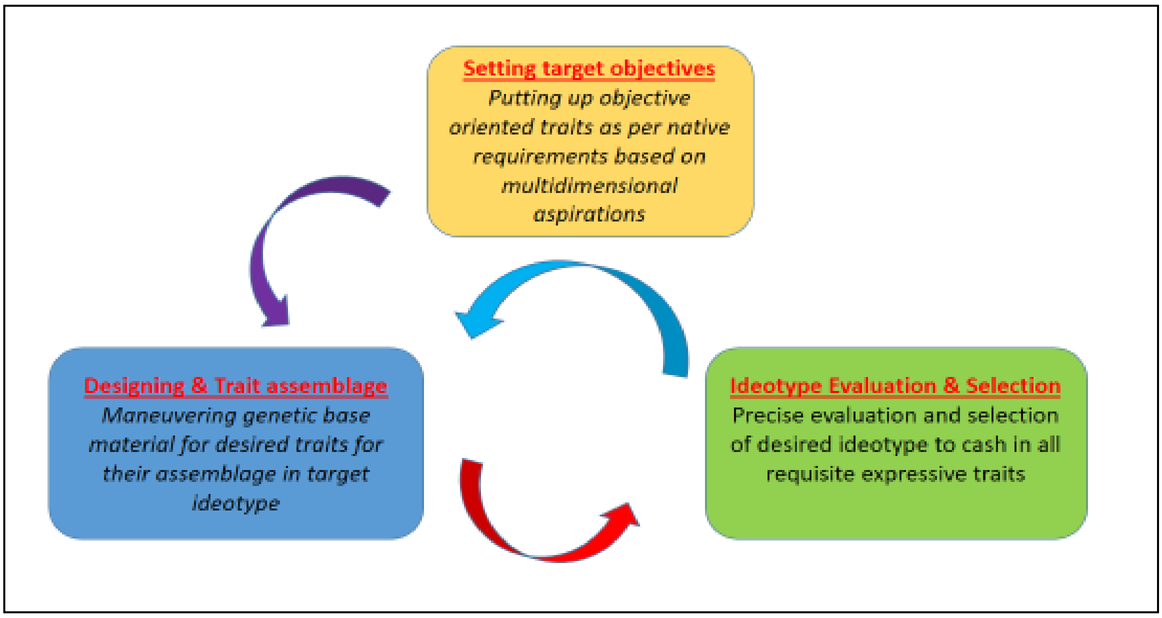


**Fig. 2: An overview of ideotype breeding**

(a) Identification and devising of a purposeful breeding objective to result in desired ideotype involving generation of a theoretical model plant with a combination of desired traits. The relative importance and trait relevance of different morphological and physiological attributes must be specified.

(b) Identification of morpho-physiological trait reservoirs or base material with all desired traits to achieve ideotyping goals and the strategies to assemble these traits in the target ideotype. The traits can be drought related parameters, biotic resilience or other relevant socio cultural aspect. The desired ideotype can be generated using trait specific hybridization programmes, genetic engineering approaches for overcoming reproductive barriers if any and molecular breeding strategies. Genetic nature of respective traits and extent trait association is a prerequisite before initiation of ideotype breeding programme.

(c) Selection of an ideal ideotype after all breeding exercise is a very vital tool in ideotype breeding. Multicriteria genotype assessment for targeted traits to ascertain their agronomic relevance and trait expression in specified environments through dedicated field evaluation trials. Every ideotype possess phenotypic plasticity which needs to be exploited to cash agronomic attributes of that particular ideotype. Ideotypes genetic gains must be complimented and adequately supported by various innate agronomic production features to maximize returns or to combat with various biotic and abiotic challenges (Desanlis *et al*., 2013). Crop management principally is often added in second. The broad overview of three basic steps involved in ideotype breeding as shown in Fig. 2.



**Merits and demerits of ideotype breeding**

*Merits:* As Ideotypes breeding exploits both physiological & Morphological variation so enhances yield attributes through these traits. Both these types of traits are specified and contribute cumulatively towards enhanced performance. Ideotype breeding is a multidisciplinary method of product development, therefore it addresses several facets of genotype refinement at once. By fusing the best genes for these features from many sources into a single genotype, it solves a variety of biotic & abiotic problems. Through the use of physiological features that can be genetically manipulated to increase yield, ideotype breeding successfully overcomes yield limitations. It is the most reliable approach of creating crop cultivars for agriecologies that have specific goals for cultivating native crops.

*Demerits:* Combining multiple desired traits into a single genotype is a difficult task due to complex genetics involved like challenges of tight undesirable linkages.Ideotype breeding takes longer time to achieve desired objectives in the making of a target ideotype with all morphological and physiological features. Ideotype breeding can never be a complete substitute for conventional breeding but a supplement to it. The goals of ideotype breeding are constantly changing as new ideotypes must be developed to satisfy the shifting and growing demands of economic items.

**Modelling in ideotype breeding:** Plant development and growth are the result of a variety of interactions and trade-offs between several important biological processes, including morphological, physiological, and biochemical ones that operate concurrently at various scales and are in competition with one another for the same resources. It is challenging to understand phenotypic construction and enhance crop performance in a variety of agro-climatic situations that are prevalent for plant growth because of these interconnections and trade-offs. Disease resilience makes it more difficult to achieve predetermined breeding goals when breeding for yield and quality. Ideotype breeding requires a precise understanding of the interactions and trade-offs between the qualities or processes that affect crop production and their genetic origins. Eco physiological models offer a perfect framework for integrative assessments of the cumulative effects of a set of traits on whole-plant and crop phenotypes, while also considering the relationships between the various traits (Bertin *et al*., 2010). The effective utilization of mathematical tools in quantifying individual trait effect on target genotypes in a particular environment is a pivotal key to develop a desired ideotype (Dingkuhn *et al*. 2007). In order to investigate trait correlations in a target population, phenotyping platforms accompanied by an ideal model describing a set of traits produce a phenotyping fingerprint. As broad-spectrum adaptability is preferred for multiple environments, even the impact of simple traits can be quantified individually or in interaction with other traits yield and adaptability. However, robust modeling ensures the development of target specific genotypes like modified practices and changing climate challenges. Using the necessary ecophysiological models, difficult-to-estimate features during phenotyping can be estimated. The main problem is to develop an effective ecophysiological model that incorporates genetic data linked to specific plant processes, and then to simulate interactions between physiological, genetic, and environmental controls to determine the value of integrated features in various contexts (Hammer *et al*., 2010).

**Target physiological traits in ideotype breeding:** Physiological traits play a vital role in determining the final yield returns from a particular crop like in wheat, $^{13}C$ was found associated high kernel number per unit area, high harvest index and total biomass (Zhou *et al* 2014). Elite rice cultivars' architectural, physiological, and agronomic characteristics can be systematically examined in order to clarify the potential reasons underlying their high yield potential, which can then be used to future rice breeding efforts (Chang *et al* 2020). Phenotyping of desired target traits followed by efficient crop modelling protocols can unravel plant mechanisms involved in final harvest development. Screening for mass adaptability for diverse environmental scenarios, understanding of canopy architecture features, photosynthetic ability and source to sink relationship is very essential in giving tenable increments to the wheat yields (Malcolm *et al.* 2013). Regulation of physiological plant processes, analysing guard cell metabolome will surely unfold the mechanism of stomatal movements and elucidate transpiration control operational in plants (Misra *et al* 2015). Number of stomata per unit area is also a reliable feature depicting photosynthetic efficiency and transpiration rates in crop plants. Earlier reproductive stage phenology during early vegetative and reproductive initiation is critical in escaping environmental challenges like heat and drought stress (Wallace *et al* 1993). When compared to the vegetative stages, the chickpea's net photosynthetic assimilation rate is 50% higher during the time of flowering and pod formation. This increased yield is likely a direct result of this increase (Devasirvatham *et al.,* 2012). Essential characteristics for successful correlations include root architecture, juvenile vigor, stomatal conductance, osmolytes, flowering period, and remobilization of water-soluble carbohydrates (Tuberosa 2012). For efficient ideotyping programme, a challenging multiple gene-controlled trait Nitrogen use efficiency should be always taken on board (Han *et al.,* 2015). Breeding refinements are being done to improve photosynthetic capacity of crops to cater global food, feed and bioenergy demands which includes encouraging light and carbon capture and designing smart crop canopies (Ort *et al.,* 2015). Efficient crop phenotyping platforms and using result oriented experimental designs shall narrow down phenotype and genotype gaps. Refinements in technologies and advanced phenotyping platforms with non-invasive techniques for measuring various growth and developmental attributes shall hasten the product delivery (Fiorani *et al.*, 2013).

**The assessment of ideotypes:** The evaluation of a given ideotype is dependent on varieties chosen in accordance with that ideotype, and it can be difficult to choose such varieties effectively. This will be made easier if features for selection are accurately and readily quantifiable, if some genetic markers are available, and if one has access to genetic resources that have been thoroughly defined. Large panels of genotypes can be characterized for the desired traits using high throughput phenotyping tools, and the corresponding trait-specific QTLs can be found. The test genotypes must be assessed in multienvironment conditions and according to the predetermined parameters in the target habitats. This assessment is often carried out in a multienvironment setup with accurate characterization of the growing circumstances, and interactions between the genotype and the environment must be taken into consideration. A precise multi-criteria evaluation aids in locating some test genotypes' key defaults that may change the underlying ideotype.

**Future prospects – Breeding by design:** Advancements in genetic engineering, marker assisted breeding, high throughput phenotyping and molecular genetics tools have enhanced efficacy of breeding gains in cultivar development in major economic crops. These techniques not only hastened breeding cycles but improved selection per se unravelled the unit effect of respective alleles towards phenotype expression. Systematic integration of these approaches is highly useful in modelling plant ideotypes to meet edaphic challenges and to understand genetic basis of all contributing agronomically important traits. Developing smart crops with efficient designs for maximizing returns under given set of cultivation practices like herbicide tolerant soybeans, transgenic for pest resistance in corn, biofortified golden rice etc. Breeding by design approach ensures expression of specific genes to control desired allelic variation for agronomically important traits. All these scientific breeding modules ultimately lead to what we call as a proper ideotype. Plant breeders will face a variety of difficulties in the upcoming years to cater food and feed demands. Notable challenges include more unpredictable weather patterns, apparent yield plateaus in some crops, links between genotype and phenotype, predictions of genotype by environment interactions, and advances in phenotyping techniques. With the help of cutting-edge tools and technology, we have been able to better comprehend the structure and function of the genome and the genetic basis for significant trait structures. Despite climate change, we anticipate that crop breeding programs around the world will continue to increase the rate of genetic gains as a result of our ability to measure and exploit quantitative trait variation in elite varieties, our germplasm repositories, and novel variation produced using targeted genetic recombination. Summation of all these attributes shall lead to an ideal ideotype with crop specific multiple trait attributes.

## CONFLIT OF INTEREST

All the authors affirm that there is no conflict of interest among them. All research activities comply with relevant legal, institutional and ethical standards.

## AUTHOR CONTRIBUTION

All the authors contributed equally in this review article.

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