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Quality-Oriented Breeding of Yardlong Bean: Integrating Pod Length, Tenderness, Fiber Composition, and Color

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Abstract Yardlong bean is an important fresh leguminous vegetable in Asia. Conventional breeding has long emphasized agronomic traits such as yield, pod number, and pod length; however, as fresh-market demand increasingly focuses on marketability and eating quality, breeding objectives are gradually shifting from yield-oriented improvement toward the coordinated enhancement of both yield and pod quality. This study focuses on four major traits-pod length, tenderness, fiber composition, and pod color-and examines their effects on marketable pod type, fresh eating quality, optimal harvest stage, and market differentiation. Pod length exhibits substantial genetic variation, but its commercial value also depends on pod straightness, uniformity, earliness, and marketable output. Tenderness is closely associated with fiber accumulation, making delayed toughening and an extended tender-harvest window more relevant to production than simply reducing fiber content. Pod color is not only an important trait for market recognition but can also serve as an auxiliary indicator for screening functional quality attributes such as anthocyanin accumulation. Future quality-oriented breeding of yardlong bean should avoid maximizing individual traits in isolation, strengthen the utilization of diverse germplasm and multi-trait evaluation, and develop appropriate trait combinations for different production systems, distribution conditions, and consumer markets. Such an approach will facilitate the development of new cultivars combining stable yield, superior marketability, and strong market adaptability.

Keywords Yardlong bean; Quality-oriented breeding; Pod length; Tenderness; Fiber composition; Pod color; Market demand

1 Introduction

Yardlong bean (*Vigna unguiculata* ssp. *sesquipedalis*) is a vegetable form of cowpea cultivated primarily for its long, tender immature pods. It is generally considered to have undergone further domestication from cultivated cowpea in Asia, with East and Southeast Asia becoming important centers of cultivation and germplasm diversity. Unlike common cowpea, which is mainly grown for mature seeds, yardlong bean is primarily produced for fresh pods and is characterized by rapid growth, a relatively long harvesting period, and convenient use as a fresh vegetable. It has therefore become an important leguminous vegetable in tropical and subtropical regions of Asia (Pidigam et al., 2021). Fresh pods also possess considerable nutritional value, with substantial variation among cultivars in protein, sugars, crude fiber, vitamins, and mineral elements. Nutritional evaluation of five yardlong bean cultivars in Bangladesh showed clear differences in protein, sugars, fiber, vitamins A and B, vitamin C, and mineral nutrients such as Ca, Fe, Mg, and Zn, indicating that yardlong bean is not only an important fresh vegetable but also has substantial potential for nutritional quality improvement (Quamruzzaman et al., 2022).

Yardlong bean breeding must still first address the fundamental requirements of stable production, high yield, and reduced losses caused by pests and diseases. Earliness, number of pods per plant, fresh pod yield, resistance to pests and diseases, and regional adaptability have therefore long been major selection targets. Considerable agronomic and resistance-related variation remains among available germplasm resources. For example, screening of yardlong bean materials for seed traits, yield performance, and disease resistance has revealed clear genotypic differences in flowering time, pod length, pod width, yield per plant, and disease response, providing a useful basis for conventional hybridization and parental selection (Shubha et al., 2022). As fresh-vegetable production has gradually shifted from a sole emphasis on yield toward greater attention to marketability and consumer quality, breeding objectives have also expanded. Recent reviews of yardlong bean improvement have increasingly

considered germplasm utilization, yield, quality, resistance, and molecular breeding within an integrated improvement framework (Li et al., 2023). Evaluation of breeding materials has likewise placed increasing emphasis on the combined use of morphological traits and genetic background rather than selecting parents solely on the basis of yield per plant or a single visible characteristic (Tira-Umphon and Pornsuriya, 2023).

Even an exceptionally long pod may have limited commercial value if it is curved, non-uniform, rapidly overmatures, or has poor eating quality. Likewise, visually distinctive pod color or high nutritional value alone is insufficient for widespread cultivar adoption if yield and marketable performance are unstable. Hybrid-breeding studies have begun to evaluate fresh pod yield together with quality-related traits such as protein content, indicating that high yield and high quality are gradually shifting from relatively independent breeding objectives toward coordinated selection (Ratnakumari et al., 2023). Against this background, this study focuses on four major traits—pod length, tenderness, fiber composition, and pod color—as key entry points for quality-oriented breeding. Pod length determines the basic marketable pod type; tenderness and changes in fiber directly influence fresh eating quality and the optimal harvest stage; and pod color links cultivar appearance with consumer recognition and specialty-market positioning. This study therefore emphasizes appropriate combinations of these traits, together with potential synergies and trade-offs in breeding and production, and examines how field marketability, eating quality, and market demand can be integrated into cultivar selection. The aim is to provide a practical reference for parental choice, breeding-material evaluation, and the definition of breeding objectives for the development of high-quality yardlong bean cultivars.

2 Marketable Pod Quality Requirements in Yardlong Bean

2.1 Quality requirements for fresh pods in commercial production

High yield is not equivalent to good marketability. Yardlong bean pods intended for the fresh market must first exhibit stable commercial appearance, including a pod length that meets local market requirements, good straightness, uniform coloration, and an intact surface, while also retaining tenderness and a certain degree of postharvest tolerance. Even when a genotype produces a high field yield, its final marketable yield may remain low if it has a high proportion of curved, diseased, overmature, or fibrous pods.

The Sri Lankan breeding line 39-9 provides a representative example. Across multiple seasons and locations, it maintained a relatively high yield of 20.3-25.3 t/ha while producing long, fleshy green pods with good adaptability and postharvest keeping quality, and it was eventually released as the cultivar “Gannoruwa A9 Mae”. Farmers preferred this cultivar mainly because of its pod characteristics, whereas consumers placed greater emphasis on color, taste, and keeping quality. In sensory evaluation, 81.3% of participants gave favorable ratings for appearance and 71.9% for taste (Malathy et al., 2017). A yardlong bean cultivar suitable for successful commercial production must therefore perform well at three successive stages: it must grow reliably in the field, present an attractive market appearance, and be accepted by consumers.

Cultivation conditions also directly affect the final proportion of marketable pods. Comparisons between protected and open-field cultivation have shown that protected production can extend the fresh-pod harvest period by 6-10 d and increase yield by 15.6%-25.1%. Under single-span protected cultivation, pods were also longer and straighter, with lower levels of pest and disease incidence (Zhang et al., 2024b). Marketable quality therefore represents the combined expression of cultivar potential and production environment. Even when breeding produces a desirable pod type, appropriate cultivation conditions are still required for that marketability to be expressed consistently.

2.2 Quality maintenance during harvest and distribution

The commercial value of fresh yardlong bean pods is highly sensitive to harvest timing. Pods suitable for fresh sale are generally harvested after sufficient elongation has been achieved, but before the seeds become visibly enlarged, while the pod wall remains tender yet retains adequate firmness. Delayed harvest can lead to seed bulging, pod-wall toughening, and increased fiber perception, whereas excessively early harvest may produce overly tender tissues that are more prone to water loss and wilting during transportation and retail display. Harvesting at the tender stage therefore requires an appropriate degree of maturity that balances eating quality with tolerance to handling and distribution.

After harvest, water loss, loss of green color, and tissue softening rapidly become major factors limiting commercial shelf life. Soontornwat et al. (2015) compared storage at 4 °C and 13 °C and found that 4 °C more effectively reduced weight loss and slowed decreases in vitamin C and chlorophyll while also delaying pod swelling. These findings indicate that effective postharvest management depends not only on low temperature itself, but also on maintaining green appearance, tissue condition, and water status.

Cold-storage studies further indicate that postharvest quality evaluation should include at least firmness, the proportion of marketable pods, chlorophyll content, vitamin C, weight loss, and surface color. Using the yardlong bean cultivar “Hai Jiang”, Jiang et al. (2018) showed that during 21 d of storage at 8℃, an appropriate concentration of 1-MCP slowed the decline in firmness and marketable-pod percentage, inhibited chlorophyll and vitamin C degradation, and reduced water loss and color change, with 1.0 μL/L showing relatively favorable performance. For cultivars intended for longer distribution chains, field evaluation of tenderness alone is therefore insufficient; postharvest retention of color, firmness, and physical integrity should also be considered.

2.3 Integrated consumer preferences for marketable pods

When purchasing yardlong bean, consumers first form an overall judgment based on pod color, length, thickness, and surface condition, while tenderness, taste, and texture become important after consumption and influence repeat purchase. Market preference is therefore inherently a multi-trait evaluation process, and superior performance in a single characteristic does not necessarily result in the highest overall acceptance.

Consumer evaluation of 20 yardlong bean and cowpea materials in Thailand provides a clear example. The local check Selected-PSU produced the longest pods in the trial, reaching 53.67 cm, but its overall satisfaction score was only approximately 3.47. By contrast, Nicro had a pod length of about 47.70 cm and was not the longest material, yet it achieved the highest overall satisfaction score of 4.11. Its scores for pod length, taste, pod color, and pod size were approximately 4.20, 3.41, 4.61, and 4.20, respectively (Benchasri and Bairaman, 2010).

A similar pattern was observed in farmer-demonstration evaluations in Kerala, India. Githika produced an average pod length of 51.0 cm and an average yield of 259 q/ha. On a nine-point sensory scale, its scores for color, appearance, aroma, tenderness, and overall acceptability were 7.70, 7.20, 6.70, 8.70, and 7.20, respectively. In contrast, another cultivar, Manjari, received a higher taste score of 7.90 (Sangeetha et al., 2022).

2.4 Key indicators determining commercial value

The commercial value of yardlong bean pods can be summarized into four major categories of indicators. The first is appearance quality, including appropriate pod length, straightness, uniformity in thickness, color consistency, and surface integrity. The second is eating quality, represented mainly by tenderness, crispness, and flavor. The third is postharvest performance, including resistance to water loss, yellowing, softening, and deterioration during shelf life. The fourth is marketable output, which reflects the proportion of total production that ultimately meets commercial quality standards. Under this framework, pod length, tenderness, fiber composition, and pod color contribute to different stages of marketable pod formation.

Among these indicators, the number of marketable or “good” pods is more closely related to actual economic return than total pod number. In an organic production trial involving five cultivars, total pod weight showed a correlation coefficient of 0.96 with the number of good pods, while the correlation between good-pod number and total pod number reached 0.98. Total pod weight was also significantly and positively associated with the number of productive branches (Putra et al., 2024). Yield increases resulting mainly from non-marketable pods therefore cannot be converted into proportional commercial returns. In practical cultivar screening, the proportion of marketable pods and marketable pod weight should be evaluated as independent indicators in addition to total yield.

Among 45 yardlong bean genotypes, pod yield per plant showed relatively strong positive correlations with the number of clusters per plant, number of pods per plant, mean pod weight, and pod length, with genotypic correlation coefficients of 0.742, 0.703, 0.669, and 0.627, respectively. The number of clusters and mean pod

weight also exerted relatively strong direct effects on pod yield per plant (Kumar et al., 2024). Commercial cultivars should therefore produce a sufficient number of acceptable pods while maintaining a reasonable balance between individual pod quality and marketable yield per unit area.

Marketable pod quality in yardlong bean results from the combined effects of appearance quality, eating quality, postharvest performance, and marketable output, all of which are continuously influenced by genotype, production environment, harvest timing, and distribution management. Pod length, tenderness, fiber composition, and pod color contribute to different components of this quality system and together determine whether fresh pods can achieve stable commercial value (Figure 1).

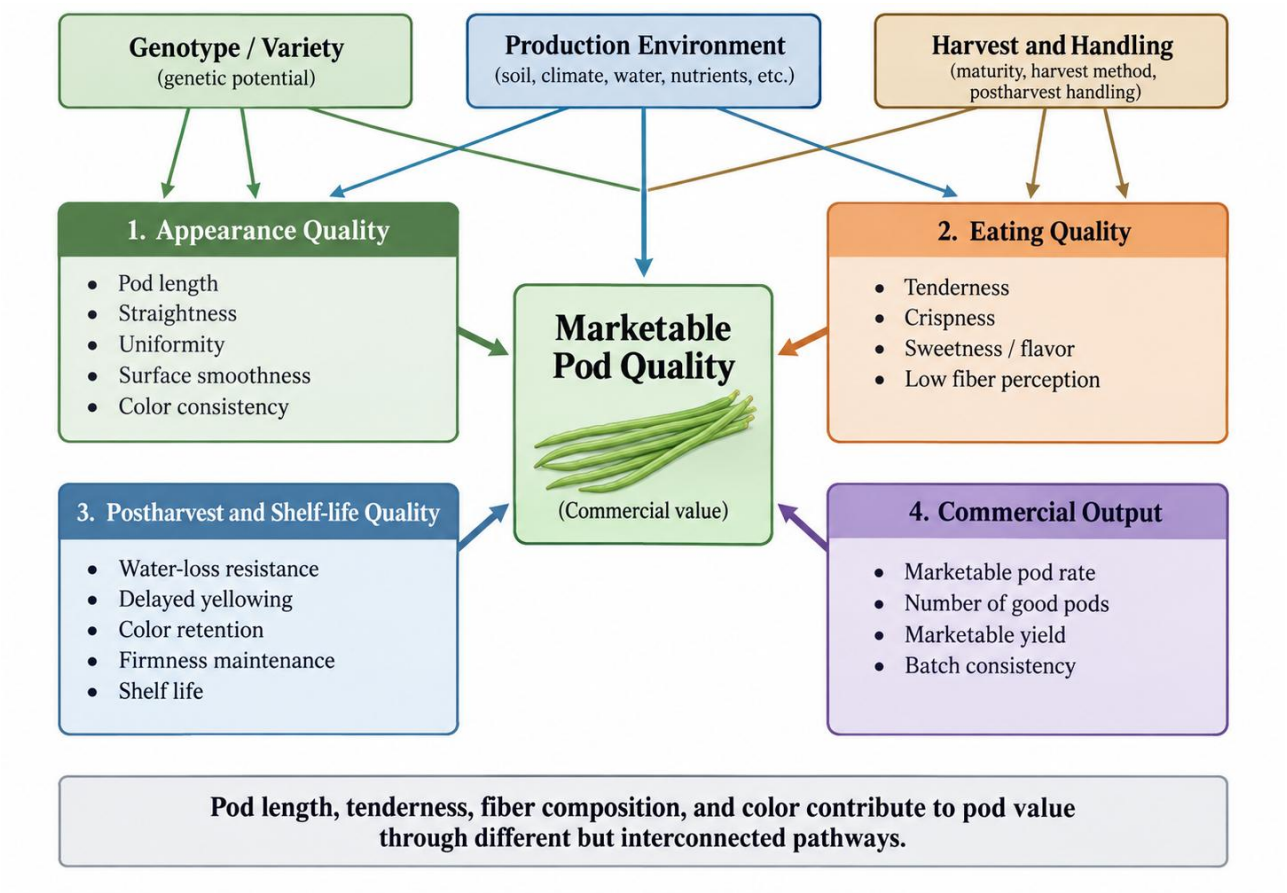


Figure 1 Framework of marketable pod quality formation in yardlong bean

3 Pod Length and Marketable Pod Type

3.1 Commercial value of pod length

In yardlong bean, pod length is first and foremost a commercial trait rather than merely an agronomic characteristic. During field selection, long pods are often among the most conspicuous features and also one of the most intuitive indicators used in fresh markets to distinguish cultivar types. The development of the modern yardlong bean pod type, which differs markedly from that of ordinary grain-type cowpea, is itself the result of long-term human selection. Nearly an eightfold difference in pod length has been observed between cultivated yardlong bean and wild cowpea, indicating that selection for increased pod length was a particularly prominent direction during the domestication of this crop (Kongjaimun et al., 2012a). This change essentially reflects a shift in cowpea utilization from mature seeds toward tender immature pods as the primary marketable organ.

In practical production, however, once pod length reaches a commercially acceptable level, the value of gaining several additional centimeters is often smaller than expected. Growers and buyers are more concerned with whether pods can reach the target market length at an appropriate time while maintaining a high number of pods per plant and stable yield. A comparison involving 29 germplasm accessions and five high-yielding cultivars

showed that superior materials were not necessarily those with the longest pods, but rather those combining relatively early first harvest, appropriate pod length, good pod-setting ability, and favorable potential fresh pod yield (Dini et al., 2019).

3.2 Genetic variation and improvement potential of pod length

One advantage of pod length as a breeding trait is the considerable variation already present within existing yardlong bean germplasm, making it well suited to direct selection. Pod length among available materials can range from just over 10 cm to nearly 60 cm. In an evaluation of 33 genotypes, pod length ranged from 14.18 to 60.08 cm, with genetic advance as a percentage of the mean reaching 85.81% (Ramkumar, 2021). Under a coastal saline ecosystem, 30 materials still exhibited a wide pod-length range of 24.38-59.31 cm, with broad-sense heritability reaching 98.47% (Haripriya et al., 2024). Although field environments inevitably influence final phenotypic expression, pod length remains a trait with relatively strong potential for improvement through repeated selection.

Pod length is also frequently an important contributor to germplasm differentiation. In a genetic divergence analysis of 41 commercial materials, pod length contributed 48.66% of the total divergence, markedly more than many other traits (Rambabu et al., 2016). Molecular-marker analysis further showed substantial genetic differences among yardlong bean germplasm, with genetic similarity coefficients ranging from 0.063 to 0.942 among 28 Indian materials (Pidigam et al., 2019). Thus, even after long-term commercial selection for long pods and uniformity, considerable exploitable variation remains within the broader germplasm pool. In parental selection, it is therefore insufficient to choose two materials simply because both produce long pods; their underlying genetic divergence and potential trait complementarity should also be considered.

The genetic control of pod length is likewise more complex than a simple single-gene model. SSR-based linkage analysis between cultivated yardlong bean and wild cowpea has identified multiple QTLs associated with pod length, including both major-effect loci and several loci with smaller effects (Kongjaimun et al., 2012b). Although pod length is relatively easy to observe in the field, stable improvement should not rely on a single phenotypic assessment. A more reliable approach is to evaluate materials across multiple years and environments while also considering parental genetic background and available information on known QTLs.

3.3 Coordination of pod length, straightness, and uniformity

For commercial production, producing a batch of fresh pods with similar length, coordinated thickness, and good straightness is more important than occasionally obtaining one or two exceptionally long pods. A genotype may have a high mean pod length, but if it also shows a high proportion of curved pods, uneven thickness, or large batch-to-batch variation, both grading and marketing can be negatively affected. Pod length should therefore be evaluated together with pod diameter, straightness, surface smoothness, and overall population uniformity.

Commercial cultivar evaluation in Nepal clearly illustrates this distinction. Great Wall 02 received a plant-uniformity score of 4.7 and produced thick-fleshed, light-green, relatively smooth and straight pods, while also showing earlier maturity, making it suitable for early-market production. By contrast, Great Wall 03 produced more pods per plant, achieved a fresh pod yield of approximately 24 t/ha, and maintained a relatively long harvesting period of 30-35 d (Pandey et al., 2020). The advantages of these two cultivars were therefore different: one emphasized uniformity, straightness, and early market entry, whereas the other emphasized pod number, high yield, and a prolonged harvest period. From a production perspective, such distinctions are more meaningful than simply comparing which cultivar produces the longest pods, because different marketing channels and production systems inherently require different marketable pod types.

3.4 Balancing pod length with harvest quality and marketability

Under field conditions, longer pods are often associated with greater individual pod weight and higher yield potential, but this relationship should not be interpreted simply as “the longer, the better.” Some genotypes allocate more growth advantage to individual pod length without necessarily maintaining a high number of pods per plant or an early harvest. In one cluster, mean pod length reached 55.35 cm, but the time to marketable harvest

was approximately 63.33 d, with only 5.81 pods per plant and a fresh pod yield of 87.12 g per plant. In another cluster, the mean pod length was slightly shorter, at 53.21 cm, but plants produced 10.99 pods and 166.67 g of fresh pods per plant (Sultana et al., 2020).

In a two-season evaluation of 25 materials, pod length showed clear positive correlations with individual pod weight, pod yield per plant, and yield per unit area, yet the time to first harvest still varied from approximately 50 d to nearly 69 d among materials (Theenan et al., 2026). For fresh-market yardlong bean, this difference has important practical implications. A genotype may eventually produce longer pods, but if achieving that length requires a substantial delay in harvest, it may lose its early-market advantage and become more prone to pod toughening and reduced marketable yield at later developmental stages.

4 Tenderness and Fiber Composition Determine Eating Quality

4.1 Tenderness and pod development

Yardlong bean is primarily marketed and consumed as immature pods, making tenderness an important trait determining fresh eating quality and market acceptance. Unlike grain-type cowpea, which is mainly used for mature seeds, yardlong bean is harvested before full pod maturity, while the pod wall remains soft and tender. Consumer evaluation of fresh pod quality generally involves several attributes simultaneously, including crispness, maturity, sweetness, appearance, and color; tenderness therefore represents one of the core components of overall marketable quality (Suma et al., 2021).

Tenderness changes markedly during pod development. Kusmiyati et al. (2026) divided F7 red-podded yardlong bean materials into three harvest stages, corresponding to 8-11 d, 14-20 d, and 23-35 d after flowering. Harvest stage had pronounced effects on most fresh-pod quality and agronomic traits. As pods developed from the early stage into the fresh-consumption stage, pod length and fresh pod weight increased, whereas marketability for fresh consumption gradually declined with further maturation. Total soluble solids increased with maturity, while shelf life decreased substantially, indicating that the optimal harvest stage for fresh consumption represents a balance among pod length, fresh weight, sweetness, tenderness, and postharvest performance.

Postharvest quality further demonstrates that tenderness should not be evaluated in isolation. Musaddad et al. (2024) compared seven yardlong bean genotypes and found clear differences in firmness, moisture content, protein content, and total soluble solids. Moisture content was strongly and positively correlated with shelf life ($r = 0.76$), whereas protein content showed a strong negative correlation with shelf life ($r = -0.79$). Practical breeding therefore requires genotypes that remain tender and crisp at the normal harvest stage while also maintaining postharvest integrity and acceptable shelf-life performance.

4.2 Fiber accumulation and the development of tenderness

The transition from tender to overmature pods in yardlong bean is fundamentally accompanied by continuous changes in pod-wall cell structure and cell-wall composition. As pods develop, structural components such as cellulose, hemicellulose, and lignin progressively contribute to cell-wall formation, thereby increasing tissue mechanical strength. If this process occurs too rapidly, pods become coarse and tough, fiber perception increases, and the tender-harvest window is shortened. For quality-oriented breeding, the key concern is therefore the rate, proportion, and spatial distribution of fiber deposition.

Thepphomwong et al. (2025) compared the distinctive local cultivar Thua Ngu with the conventional cultivar Raya. At the young-pod stage, cellulose contents in Thua Ngu and Raya were 9.84% and 10.70%, respectively; hemicellulose contents were 4.94% and 4.33%; and lignin contents were 0.34% and 0.70%. At maturity, lignin content increased to 1.10% and 3.81%, respectively. The two cultivars also differed markedly in pod-wall cell size, density, and arrangement. Fresh-pod texture therefore cannot be explained simply by the assumption that lower fiber content always means greater tenderness. The relative proportions of fiber components, cellular structure, and the pattern of fiber deposition within the pod wall also contribute to final eating texture.

4.3 Genetic basis of tenderness-and fiber-related traits

Genetic studies of tenderness in yardlong bean have established a relatively clear research framework. Kongjaimun et al. (2013) developed segregating populations from cultivated yardlong bean JP81610 and wild cowpea JP89083 and measured pod puncture hardness at 9 d after flowering. The cultivated parent had an average hardness of 0.70 ± 0.35 kg/cm², whereas the wild parent reached 2.81 ± 0.52 kg/cm², approximately four times higher. Three tenderness QTLs were identified, among which Psn7.1 on LG7 had the strongest effect and explained approximately 45%-50% of phenotypic variation across different populations. These tenderness QTLs were co-localized with pod-length QTLs, and alleles derived from cultivated yardlong bean simultaneously increased pod length and tenderness, suggesting a degree of genetic coordination between long pods and tender pods during yardlong bean domestication.

Suanum et al. (2016) extended this genetic relationship to pod-wall fiber composition. In populations derived from crosses between yardlong bean and wild cowpea, QTLs associated with cellulose, hemicellulose, and lignin were identified. The loci qCel7.1, qHem7.1, and qLig7.1 on LG7 were located within the same or adjacent genomic regions and explained approximately 15.48%, 61.11%, and 47.80% of phenotypic variation, respectively, in one F2 population. This chromosomal region also overlapped with a major pod-shattering locus. These findings indicate that tenderness, fiber formation, and pod shattering are not entirely independent traits, but may be controlled by shared or tightly linked genetic factors during yardlong bean domestication.

Watcharatpong et al. (2020) subsequently narrowed the corresponding genomic region using segregating materials including 309 F2 individuals and 334 F2:3 families. In most cases, cellulose, hemicellulose, and lignin were each controlled by one major QTL together with a smaller-effect QTL, while the major loci for all three fiber components consistently clustered within the same chromosomal region. Across different populations, the major fiber QTLs explained approximately 30% to more than 50% of phenotypic variation. The study further proposed VuBGLU12 and VuMYB26b as candidate genes potentially involved in pod-wall fiber formation and pod-shattering regulation.

4.4 Delaying toughening and extending the tender-harvest window

The key challenge in quality-oriented breeding is how to keep pods tender for longer and delay the onset of overmaturity. In large-scale production, it is difficult to harvest all pods at exactly the same stage of maturity. If a cultivar undergoes rapid fiber accumulation, even a slight delay in harvest can result in coarse and overmature pods. Delaying pod toughening and extending the tender-harvest window therefore has greater practical breeding value than simply reducing fiber content at a single sampling point.

Improvement of tenderness must also be coordinated with yield, nutritional quality, and overall marketability. Widyawan et al. (2020) compared 21 yardlong bean genotypes and found that total pod weight, individual pod weight, and pod length were generally negatively correlated with protein content and total dietary fiber, indicating that high yield, long pods, and nutritional composition do not necessarily improve simultaneously. By contrast, Sreeja et al. (2024) reported high heritability together with high genetic advance for traits including pod length, individual pod weight, yield, crude fiber, and crude protein in Fusarium-wilt-resistant BC2F1 materials, suggesting substantial potential for selection.

In practical breeding, basic commercial traits such as pod length, straightness, yield, and disease resistance can first be secured, after which the rates of firmness increase and fiber accumulation can be compared across several consecutive harvest stages. For existing commercial materials, local germplasm and genetically more distant accessions should also be introduced appropriately to broaden variation in tenderness and fiber composition. The ultimate breeding target is to identify genotypes that remain tender, toughen slowly, and maintain a stable pod type throughout the normal commercial harvest period, which more closely reflects the practical objectives of quality-oriented yardlong bean breeding.

From the dynamic perspective of pod development, the key breeding target is to modify the temporal relationship between declining tenderness and increasing fiber deposition. Ideally, the transition from a marketable tender pod

to a coarse, overmature pod should be delayed as much as possible, thereby expanding the optimal harvest stage from a narrow time point into a relatively stable harvest window (Figure 2).

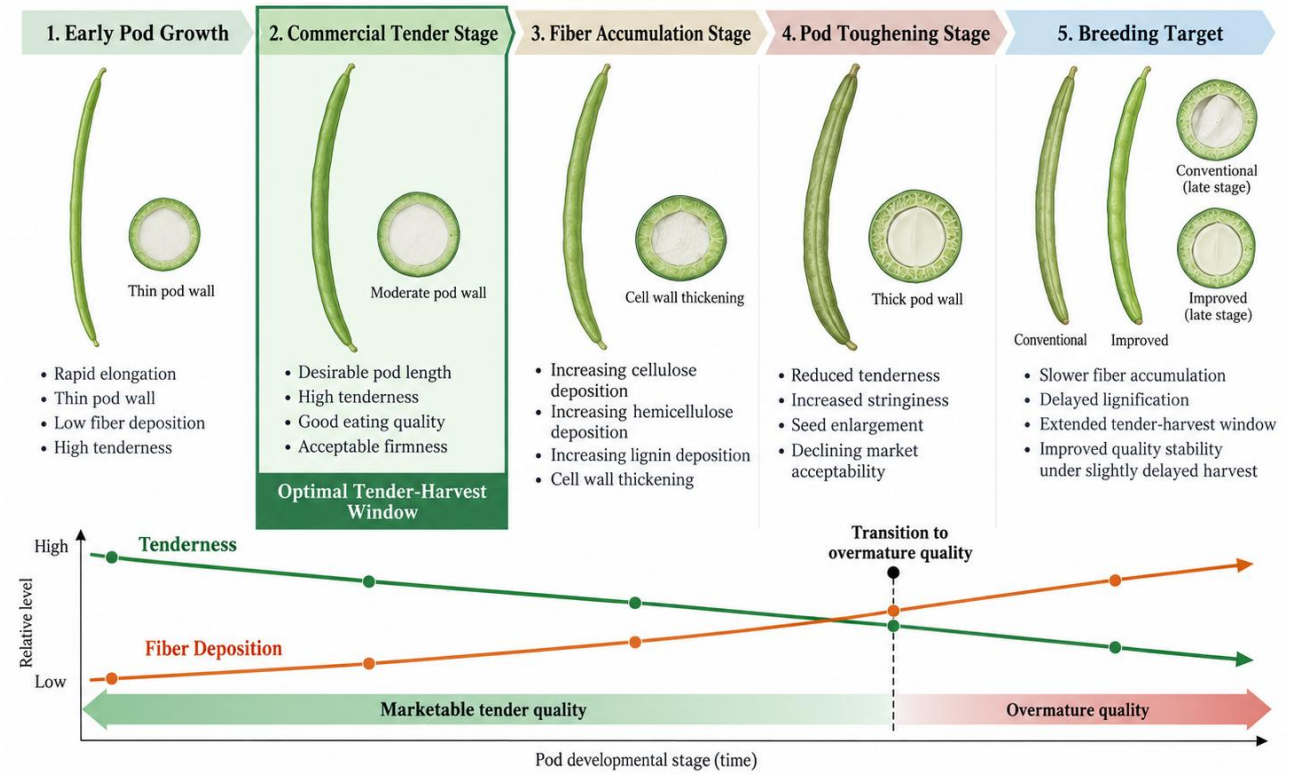


Figure 2 Developmental basis of pod toughening and breeding targets for delayed toughening in yardlong bean

5 Pod Color Differentiation and Market Positioning

5.1 Germplasm diversity in pod color

For fresh-market yardlong bean, pod color is one of the most readily observable appearance traits in the field and one of the most immediately recognizable characteristics for consumers in the marketplace. Existing germplasm is not limited to a single green type, but includes light green, dark green, green pods with purple tips, purple pods, and various intermediate forms. A survey of 39 yardlong bean accessions from coastal regions of India showed that 28 accessions had light-green pods, accounting for 72%; six had light-green pods with purple tips, accounting for 15.4%; four had dark-green pods; and one exhibited purple pods with green tips. Green remains the dominant commercial type, but purple and mixed-color forms are clearly present in local germplasm and represent valuable sources for specialty breeding (Kamala et al., 2014).

Color variation can be further expanded through hybridization and continuous selection. In an early purple-pod breeding population, approximately 1 200 segregating plants showed marked color variation, with purple phenotypes ranging from dark purplish red and deep purple to purple-green striped, intense red, dark red, and dull red types. Selection produced 90 expected purple-pod lines, from which 15 candidate lines were identified (Kuswanto et al., 2013). Pod color is therefore not simply a binary green-versus-purple trait, but rather a continuously variable characteristic with substantial selection potential. In practical breeding, the most valuable materials are not necessarily those with the darkest color, but those that combine stable and uniform coloration with an appropriate pod type and favorable production traits.

5.2 Genetic regulation and stable selection of pod color

The primary purpose of understanding the genetic basis of pod color is to determine whether color can be inherited stably and whether early-generation assisted selection is feasible. Studies involving crosses between green- and purple-podded cowpea have mapped the fresh-pod color locus to chromosome 5. Using 150 F2 individuals, a high-density genetic map containing 9,493 SNPs was constructed, and the pod color locus was

narrowed to a region containing anthocyanin-related genes. A dCAPS marker capable of distinguishing pod-color phenotypes was also developed (Li et al., 2021). For stable target colors such as purple and red-purple, future breeding could therefore combine visual selection with molecular markers, reducing repeated dependence on mature phenotypic evaluation in early-generation populations.

This chromosomal region has also shown good consistency across different cowpea studies. Mapping of black seed coat and purple pod-tip color identified the MYB113 gene cluster as being closely associated with pigmentation, with Vigun05g039300 showing relatively high expression in developing pods and being proposed as an important candidate gene controlling purple pod-tip coloration (Herniter et al., 2018). Integrated metabolomic and transcriptomic analyses further showed that purple cowpea pods mainly accumulated delphinidin 3-O-glucoside and cyanidin 3-O-glucoside. In the same study, 56 differentially accumulated metabolites and 4,142 differentially expressed genes were identified, and multiple MYB, bHLH, and WD40 regulatory factors were found to participate jointly in pigment formation (Li et al., 2020).

5.3 Pod color as a market and consumer preference trait

There is no single pod color that is universally superior across all markets. An early direct survey of 45 household consumers in Bandung, Indonesia, showed that consumers from all three income groups placed considerable importance on light-green pods. They also preferred pods of medium maturity, 40-60 cm in length, round in shape, of medium thickness, and with a smooth and glossy surface (Soetiarso and Marpaung, 1995). Consumers therefore respond not to color alone, but to an overall commercial image formed by color, length, maturity, shape, and surface appearance.

Such preferences also vary among market segments. Conjoint analysis of ethnic vegetables, including yardlong bean, showed that consumers from different cultural backgrounds assign different levels of importance to external quality attributes such as freshness, appearance, size, and firmness, and that preferences are also influenced by country of origin and cultural background (Campbell et al., 2016). It is therefore inappropriate to define green pods simply as a conventional type and purple pods as an upgraded type, or to assume that darker color automatically confers greater market value. Mainstream wholesale markets may place greater emphasis on familiar, uniform, and stable green types, whereas specialty retail, direct marketing, and functional-vegetable markets may be more receptive to visually distinctive purple or red-purple products.

Whether a distinctive pod color can ultimately be developed into a successful cultivar also depends on production stability. Evaluation of six purple-podded yardlong bean candidate lines across six environments showed that BU1 and BU6 produced fresh pod yields of approximately 9.18 and 8.81 t/ha, respectively, and exhibited relatively broad adaptation. BU5 reached approximately 10.03 t/ha under high-productivity environments, whereas BU3 had the highest anthocyanin content (Zulfarosda et al., 2020). Pod color can therefore support market differentiation, but a commercially viable purple-podded cultivar must still meet the most fundamental production requirements of stable yield, environmental adaptation, and consistent color expression.

5.4 Relationships between pod color and nutritional quality

Among nutritional traits, anthocyanin content is the component most readily associated with pod color, but color should not be treated as equivalent to overall nutritional value. A comparison of 15 green- and purple-podded yardlong bean genotypes showed that Fagiola 2 had relatively high anthocyanin and carotenoid contents, whereas Peleton achieved the higher yield. Anthocyanin content was not significantly correlated with yield components, while carotenoid content showed positive relationships with several traits, including pod length, individual pod weight, and chlorophyll content (Reswari et al., 2019). Purple-podded materials can therefore serve as valuable sources for high-anthocyanin breeding, but darker pod color alone cannot be used to infer higher yield, superior overall nutritional quality, or greater commercial value.

One major advantage of pod color is its potential use as a low-cost preliminary phenotype for anthocyanin screening. Analysis of 558 yardlong bean samples ranging from light green to deep purple showed that total anthocyanin content ranged from a minimum of 0.196 A/gFw in green materials to a maximum of 19.451 A/gFw

in purple materials, representing nearly two orders of magnitude of variation. Models developed using L*, a*, and b* color values, glossiness, and reflectance spectra from 400 to 700 nm achieved a correlation coefficient of 0.900 for anthocyanin prediction (Bunluephan et al., 2023). Large breeding populations could therefore be rapidly stratified at early stages using pod color and portable color measurements, followed by chemical analysis of anthocyanins and other quality components in a smaller number of selected materials, thereby reducing the cost of quality screening.

Pod-color breeding should ultimately be aligned with the intended consumer group and marketing channel. Green-podded types are more appropriately positioned for stable marketability and broad acceptance in mainstream fresh markets, while light- or bright-green types may emphasize visual freshness and regional preference. Purple and red-purple types, in contrast, are better suited to market differentiation and the functional value associated with anthocyanins. Because different pod colors correspond to different levels of consumer acceptance, specialty value, and breeding emphasis, color selection is fundamentally also a form of target-market selection (Figure 3).

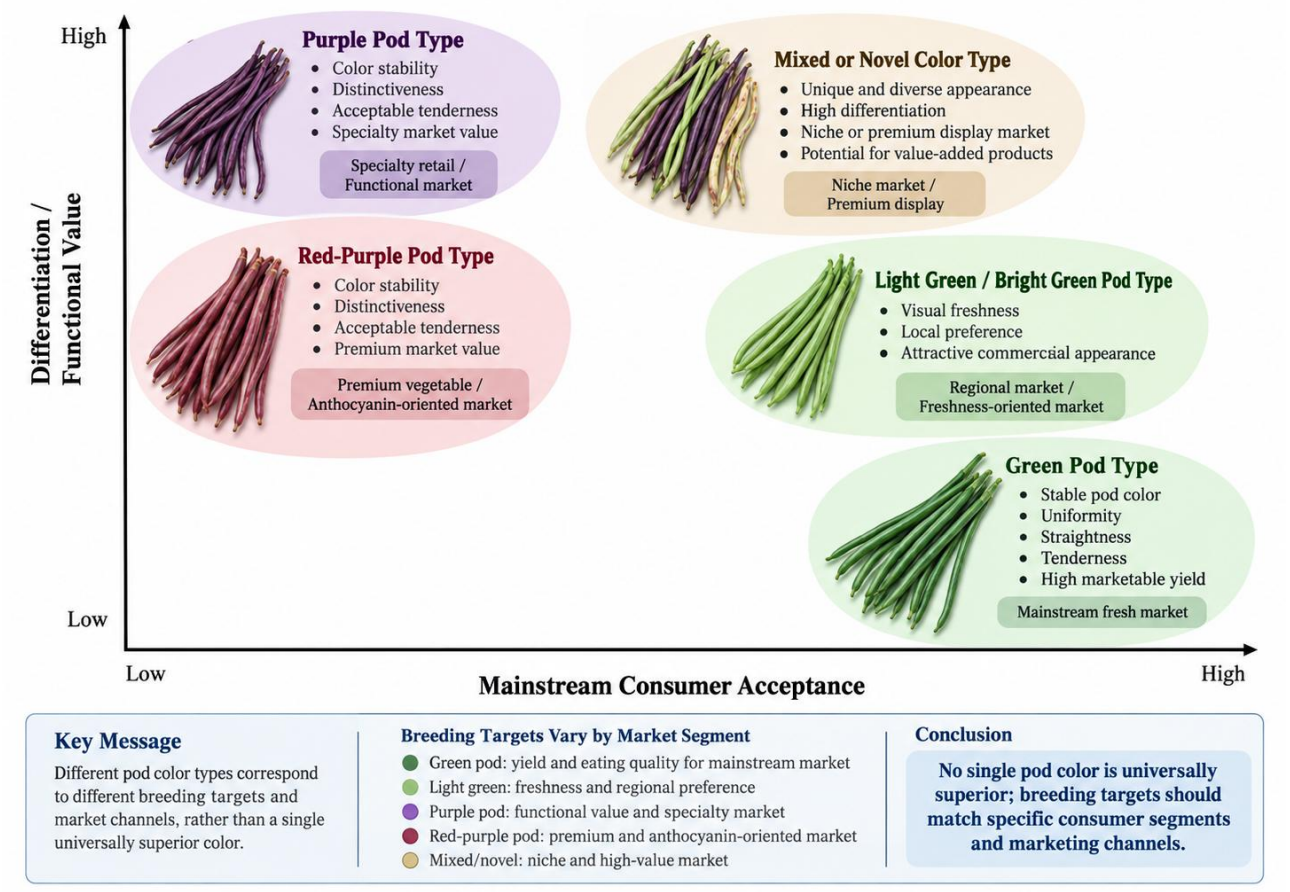


Figure 3 Market differentiation and breeding positioning of yardlong bean pod color types

6 Coordinated Multi-Trait Improvement for Quality-Oriented Breeding

6.1 Limitations of single-trait selection

Commercial breeding of yardlong bean has long emphasized pod length, pod weight, yield, and uniformity. However, continuous selection around only a few visible traits can gradually reduce phenotypic differentiation among commercial materials. Truong et al. (2026) compared 20 commercial F1 hybrids from Vietnam, Thailand, and China and evaluated 17 morphological traits. Phenotypic variation among materials was driven mainly by quantitative pod traits such as pod length and pod weight. Pod length ranged from 26.18 to 40.19 cm, and individual pod weight ranged from 11.11 to 14.17 g, whereas total soluble solids still varied from 4.92% to 7.08%. More importantly, RAPD analysis detected 79.42% polymorphism, with genetic similarity coefficients ranging

from 0.46 to 0.96. Some hybrids with similar external appearance were clearly differentiated at the molecular level. Evaluating parental value solely on the basis of pod length and visible appearance may therefore overlook hidden quality differences and may also lead to inaccurate estimation of genetic complementarity between parents.

Widaryati et al. (2023) compared 13 F7 red-podded yardlong bean lines with two check cultivars. Check 2 had the longest mean pod length in the trial, approximately 65.6 cm, but produced a yield of only about 7.1 t/ha. By contrast, FPT A 3-4-10-1 had a slightly shorter pod length of approximately 62.5 cm, but could be harvested at about 45.2 d, produced 29.8 pods per plant, and achieved approximately 546.1 g pod weight per plant, equivalent to a yield of about 14.6 t/ha, nearly twice that of the longest-podded check. Another line, FPT A 3-4-7-1, had a pod length of approximately 60.8 cm but likewise combined relatively early harvest with high yield. In market-oriented breeding, the truly valuable target is therefore a suitable combination of "sufficient pod length + early harvest + high pod number + high yield", rather than simply maximizing pod length.

Coordinated changes in multiple traits are also a fundamental feature of cowpea domestication and improvement. Wu et al. (2024) resequenced 344 grain- and vegetable-type cowpea accessions and identified 39 loci associated with 10 important agronomic traits, together with more than 541 genomic regions potentially subjected to domestication or improvement selection. Different selection processes simultaneously involved pod length, seed number per pod, seed weight, soluble sugars in pods and seeds, and crude protein content. A locus associated with reduced pod shattering was selected together with a nearby stress-resistance-related locus, suggesting that improved shattering resistance may have been accompanied by the loss of part of the original stress tolerance. Breeding is therefore not simply a process of continuously increasing desirable traits, but rather one of finding more appropriate combinations among multiple favorable traits and their potential trade-offs.

6.2 Coordinated configuration of pod length, tenderness, fiber, and color

Pod length itself is associated with several yield components. Edematie et al. (2021) investigated the inheritance of pod length using P1, P2, F1, F2, and backcross generations from two common cowpea × yardlong bean crosses. Pod length showed correlation coefficients of 0.84 and 0.77 with individual pod weight, 0.41 and 0.30 with seed number per pod, and 0.61 and 0.29 with seed weight per pod in the two crosses, respectively. In one cross, the yardlong bean parent TVu 6642 had pods 28.2 cm longer than those of the common cowpea parent, but it also produced fewer peduncles and pods per plant. These results indicate that increasing pod length can improve certain components of marketability and yield, but does not automatically ensure simultaneous improvement in pod number per plant, earliness, or overall yield.

Ihsanto et al. (2023) evaluated F7 red-purple-podded progenies derived from crosses between purple- and green-podded parents and simultaneously measured pod length, pod color, texture, sweetness, and anthocyanin content. The purple-podded check had a sweetness level of only 3.00 °Brix but an anthocyanin content of 13.57 ppm. Some hybrid progenies substantially increased sweetness while retaining a red-purple appearance. For example, FPT A 3-4-7-1 reached 6.73 °Brix with 7.58 ppm anthocyanin, while FPT A 3-4-8-2 reached 6.00 °Brix with 7.88 ppm anthocyanin. Breeding for distinctive pod color does not necessarily require sacrificing eating quality, but increased sweetness and maximum anthocyanin content do not necessarily occur together. For specialty fresh markets, a more practical objective is therefore to combine recognizable color, acceptable sweetness, and good tenderness rather than simply pursuing the darkest pod color or the highest anthocyanin concentration.

Zhang et al. (2024a) used a high-density genetic map containing 514,227 SNPs and 2,084 bin markers to identify 20 QTLs associated with anthocyanin, vitamin E, soluble protein, pod length, and seed-related traits in a yardlong bean recombinant inbred-line population. Individual loci explained 7.58%-56.03% of phenotypic variation. Major loci such as qANT5 and qPL3 were consistently detected in 2020, 2021, and combined-environment analyses, and VuANT1 was identified as an important gene regulating anthocyanin accumulation. Future quality-oriented breeding could therefore combine easily observable traits such as pod length and pod color with molecular markers, while incorporating tenderness and the rate of fiber accumulation into field and laboratory evaluation,

thereby gradually establishing an integrated selection system covering pod type, eating quality, fiber characteristics, and color.

6.3 Joint selection for field performance and quality

Multi-trait breeding first requires expansion of the evaluation criteria. Evaluating only pod length, individual pod weight, and yield per plant can easily overlook nutritional and quality differences that are not visually apparent. Choi et al. (2024a) conducted a combined agronomic and biochemical evaluation of 35 yardlong bean accessions from China, Korea, Myanmar, and Thailand. Crude fiber content ranged from 4.10% to 6.51%, dietary fiber from 16.71% to 23.49%, protein from 22.45% to 28.11%, and fat from 0.59% to 2.00%. Vitamin C showed an even wider range, from 0.23 to 3.04 mg/g, representing more than a tenfold difference. Considerable variation was also observed in phenolics, tannins, saponins, and antioxidant capacity, and multivariate analysis classified the 35 accessions into four distinct groups. Thus, two yardlong bean materials that appear similar in the field may differ substantially in internal nutritional and functional quality, indicating that quality-oriented breeding should incorporate selected biochemical evaluations into parental screening.

Although pod color is highly suitable as a market-recognition trait, it should not be used directly as a substitute for nutritional quality. Choi et al. (2024b) evaluated 14 yardlong bean accessions differing in pod and seed-coat color and found that coefficients of variation among different biochemical traits ranged from 1.36% to 51.01%. YLB14 contained 2.62 mg/g vitamin C and 21.45% dietary fiber. Pod and seed-coat color significantly affected total phenolics and antioxidant indicators such as DPPH, ABTS, and reducing power, but had no significant effect on most nutritional traits, with dietary fiber being one of the few exceptions. Purple, red, or other dark-colored pods can therefore serve as important appearance traits for specialty markets, but they should not be interpreted directly as indicators of superior nutritional value without supporting measurements.

Field selection should likewise focus on materials that simultaneously satisfy multiple production criteria rather than identifying separate materials that are simply the earliest, longest, or highest yielding. Kusmiyati et al. (2025) evaluated 15 F8 red-podded yardlong bean materials and found clear genotypic differences in flowering time, harvest time, pod length, pod width, pod number per plant, and pod weight per plant. Among them, FA 1-1-10-1-6 outperformed the check cultivar in several traits, including flowering time, harvest time, pod number per plant, and pod weight per plant, and was therefore considered a promising donor for subsequent hybridization.

6.4 Selection priorities in quality-oriented breeding

Quality-oriented breeding can benefit from multi-trait selection indices rather than relying solely on sequential elimination for individual traits. Basavaraj et al. (2026) evaluated 250 cowpea accessions under heat stress using several multi-trait indices, including MGIDI, MTSI, MTMPS, and FAI-BLUP, to jointly assess yield, yield components, and physiological adaptation. Under heat stress, only 147 accessions were able to flower and set seed normally. Across the different indices, 29 materials were identified as having superior overall performance, of which six were consistently selected by all evaluation systems. Based on the predicted selection response, genetic gains for grain yield, pod number per plant, and seed number per pod reached 18.7%, 11.2%, and 8.5%, respectively. This approach provides a direct reference for quality-oriented breeding in yardlong bean: an ideal marketable type can first be defined, the desired direction of each trait can then be specified according to its importance, and selection can be based on the distance from the ideal type rather than on whether any single trait reaches the maximum value.

Parental selection should likewise emphasize trait complementarity. Zaki and Radwan (2022) selected five parents from 28 cowpea materials and developed six crosses. Asian Introduction and Commercial 1 performed well for pod length, pod diameter, seed number per pod, and seed weight per pod, whereas Colossus, Cream 7, and Dokki 331 showed advantages in pod number per plant and seed yield per plant. Their progenies therefore provided opportunities to recombine these favorable traits, and the crosses Cr7 × Com1 and D331 × AI were identified as particularly promising. The key to parental selection is not that both parents are individually “good”, but that one parent can compensate for traits lacking in the other.

For yardlong bean, a practical hierarchical selection scheme can be established on this basis. The first level should secure basic marketability, including yield, pod number per plant, appropriate pod length, straightness, and harvest time. The second level should focus on retention of tenderness, rate of fiber accumulation, sweetness, and shelf-life performance. The third level can then incorporate green, red, purple, or other pod colors according to the target market, together with nutritional and functional quality traits. Haque et al. (2021) reported that pod yield per plant, individual pod weight, and pod number per plant showed high heritability and genetic advance among 25 yardlong bean materials, while yield per plant was significantly and positively correlated with pod number per plant, pod length, and seed number per pod. These stable and easily measured agronomic traits are therefore well suited for early-stage screening in large populations, whereas more costly traits such as tenderness, fiber composition, anthocyanin content, and other quality indicators can be evaluated later in smaller selected populations. The ultimate breeding objective is to develop cultivars with an appropriate combination of traits for the target production environment and consumer market, including suitable pod length, prolonged tenderness, moderate fiber formation, market-preferred pod color, stable yield, and consistent marketability.

7 Conclusions and Breeding Priorities

7.1 Major insights into pod quality in yardlong bean

The central principle of quality-oriented breeding in yardlong bean is to regard the fresh pod as an integrated commercial organ. From the producer's perspective, a high-quality pod should reach an appropriate length, remain straight and uniform in thickness, and retain good tenderness during the normal harvest period. For distribution, it should also resist water loss, discoloration, and rapid toughening. From the consumer perspective, pod color, texture, sweetness, and overall appearance become additional concerns. Commercial value is therefore determined by a stable combination of multiple traits that jointly meet the requirements of production, distribution, and consumption.

Pod length, tenderness, fiber composition, and color each have their own genetic basis, but they are not completely independent. Pod length is clearly associated with several yield components, yet excessive selection for longer pods may compromise earliness, pod number per plant, or uniformity. Tenderness is closely related to fiber formation in the pod wall, but the lowest possible fiber content does not necessarily result in the best commercial quality because pods must retain sufficient structural strength. Pod color provides strong market recognition, but darker color does not necessarily indicate higher overall nutritional value or greater commercial value. Quality-oriented breeding in yardlong bean should therefore shift from "single-trait improvement" toward "marketable pod-type design", in which appropriate combinations of traits are configured for a clearly defined target market.

7.2 Priority traits for future quality-oriented breeding

From the perspective of practical production and cultivar utilization, future breeding should first continue to secure basic marketability. Yield, disease resistance, and regional adaptability remain prerequisites for large-scale cultivar adoption, while pod length should shift from a "longer is better" target toward an appropriate range that meets the needs of the target market. In practical selection, pod length should be evaluated together with straightness, uniformity in thickness, pod number per plant, time to first harvest, and proportion of marketable pods. Once the market-recognized pod length has been reached, the value of gaining a few additional centimeters is usually lower than that of improving uniformity and marketable-pod percentage. Breeding evaluation should therefore place greater emphasis on the stability of the overall pod batch rather than on the performance of a few exceptionally long pods.

A second priority should be delayed toughening. For fresh-market yardlong bean, "remaining tender for longer" has greater production value than being "extremely tender" at a single sampling point. Future selection systems could incorporate changes in firmness, rates of fiber accumulation, and maintenance of external quality across several time points before and after the normal commercial harvest stage, with priority given to materials that still retain acceptable eating quality under slightly delayed harvest. This would both extend the tender-harvest window and reduce the proportion of coarse, overmature pods resulting from delayed picking. Evaluation of tenderness

should also be integrated with shelf-life performance so that excessive softness does not compromise pod integrity during transport and retail.

A third priority is to assign different weights to pod color and functional quality according to market type. Mainstream fresh markets should continue to prioritize familiar, stable, and uniform commercial coloration, whereas distinctive purple and red-purple pod types are better suited to specialty retail, functional-vegetable, or differentiated consumer markets. Pod color can serve as a rapid indicator for visual recognition and preliminary screening of certain functional components, but it cannot replace direct evaluation of nutritional quality, flavor, or yield. A practical order of priorities for future quality-oriented breeding is therefore to first ensure that a cultivar can be grown, harvested, and marketed successfully, and then incorporate prolonged tenderness, distinctive pod color, and nutritional quality according to the intended market.

7.3 Strengthening the utilization of diverse germplasm resources

Long-term directional selection for long pods, high yield, uniformity, and green marketable pods has gradually increased phenotypic similarity among some commercial yardlong bean materials. If future breeding continues to rely repeatedly on crosses among existing major cultivars, the scope for further quality improvement may become increasingly limited. Greater use should therefore be made of landraces, distinctive pod-color materials, germplasm with unusual texture, and resources that are genetically distant from commercial cultivars, so that unique traits related to tenderness, fiber accumulation, color, or adaptation can be reintroduced into breeding populations.

The value of local germplasm should not be limited to conservation; its specific breeding contribution should be clearly identified. Some materials may not fully match the pod type currently preferred by mainstream markets, but may possess desirable characteristics such as slow toughening, distinctive crispness, stable purple coloration, or strong stress tolerance. Such materials are more appropriately used as donor parents than as commercial cultivars directly. In practical breeding, the core advantage of each donor can first be identified, after which undesirable traits can be progressively reduced through hybridization, backcrossing, and repeated selection, allowing distinctive quality attributes to be introduced into a stable commercial genetic background.

Germplasm evaluation should likewise expand from simple agronomic recording toward an integrated framework combining field performance, quality traits, and intended market use. In large populations, low-cost traits such as pod length, color, straightness, and maturity can be used for preliminary screening. In smaller advanced populations, additional measurements of firmness, fiber composition, total soluble solids, anthocyanin content, and shelf-life performance can then be incorporated.

7.4 Aligning breeding objectives with production and market demand

Different production regions and marketing systems do not require the same ideal cultivar. Cultivars intended for large-scale wholesale markets and long-distance transportation should place greater emphasis on pod uniformity, transport tolerance, stable yield, and a wider harvest window. Cultivars intended for local fresh markets can assign greater weight to tenderness, sweetness, and earliness. For specialty retail or functional markets, differentiated traits such as purple or red-purple pod color, high anthocyanin content, or distinctive eating texture can be given greater importance. Quality improvement can be translated into commercial value only when breeding objectives are matched to specific marketing scenarios.

When new breeding lines enter advanced comparative trials, the target marketable type should first be defined before evaluation weights are assigned. For example, a conventional green-podded cultivar can prioritize yield, appropriate pod length, straightness, prolonged tenderness, and the proportion of marketable pods. A specialty purple-podded type should first meet these basic requirements and can then be further evaluated for color stability, anthocyanin content, and consumer recognition. Different cultivar types do not need to maximize the same indicators; the key is for each type to develop a stable, clearly defined, and interpretable combination of quality traits.

Overall, future quality-oriented breeding of yardlong bean should move away from selecting simply for the longest, most tender, or darkest-colored materials and toward developing cultivars with clearly defined

combinations of target traits. For practical breeding and production, priority should be given to genotypes that consistently combine appropriate pod length, uniform pod type, prolonged tenderness, slow fiber accumulation, market-preferred color, stable yield, and high marketability under the target production environment. Only by effectively linking germplasm resources, field production, quality evaluation, and market demand can quality-oriented breeding progress from individual trait improvement toward the development of new cultivars that are suitable for cultivation, commercially marketable, and sustainable in long-term use.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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