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Development of crop-specific vegetable seedling quality assessment systems using z-score standardization and the analytic hierarchy process

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Abstract

Background

Commercial vegetable nurseries require assessment criteria that can accommodate multiple seedling traits while accounting for crop-specific growth patterns and production objectives. This study developed crop-specific seedling quality assessment systems for pepper, tomato, watermelon, kimchi cabbage, and cucumber by integrating expert-derived trait priorities with standardized trait scores.

Results

Candidate traits were identified from published studies, nursery practice, and consultation with nursery growers. From 2022 to 2024, 19–26 nursery professionals per crop completed pairwise-comparison surveys. After consistency screening, judgments were aggregated by geometric mean and trait weights were derived using the analytic hierarchy process. Quantitative traits other than uniformity were standardized as z-scores and converted to six-level scores (1.0–0) according to crop-specific target ranges and the distance from those ranges. Uniformity was scored directly on its original 0–1 scale, and qualitative traits were scored using predefined criteria. Weighted trait scores were summed and converted to a 0–100 scale. Consistency ratios of the crop-level group matrices ranged from 0.0061 to 0.0720. Disease and pest status received the greatest weight in all crops, followed by relatively high weights for uniformity and seedling age. The first flower node in pepper, the first inflorescence node in tomato, and leaf length and width in kimchi cabbage represented crop-specific developmental or morphological characteristics.

Conclusions

The proposed systems use a common calculation framework while retaining crop-specific trait sets, weights, and target ranges. They provide an initial quantitative framework for nursery quality management, comparison among production lots, and communication of assessment criteria between nursery operators and growers. Further validation is required to determine whether the composite scores predict transplant establishment, subsequent growth, yield, and marketable quality.

Background

Seedling quality established during nursery production can influence transplant establishment and early growth and may also affect subsequent productivity [1–3]. In paprika, tomato, and watermelon, nursery environment, production system, and container size have altered seedling attributes, with corresponding differences observed after transplanting in vegetative growth, early yield, or harvest timing [4–7]. In pepper, nursery duration affected plant height, node number, leaf area, fresh mass, and dry mass before transplanting and was also associated with differences in post-transplant growth and marketable yield

[8]. Cucumber seedlings produced under different nursery systems likewise differed in post-transplant growth rate and productivity [9]. In tomato, production systems altered shoot growth, compactness, the Dickson quality index (DQI), and root development before transplanting, together with early post-transplant differences in plant height, node number, and leaf number [10]. Collectively, these findings indicate that morphological and physiological conditions established during nursery production can carry over into later crop performance. However, the traits relevant to seedling quality and their appropriate ranges vary with crop growth habit and production objectives. Assessment criteria should therefore be defined on a crop-specific basis.

Seedling quality has been evaluated using plant height, stem diameter, leaf area, fresh and dry mass, root traits, and composite quality indices. However, no single indicator captures the full range of morphological and physiological attributes, and the usefulness of individual indicators can vary with crop, nursery conditions, and assessment purpose [11, 12]. In a comparison of tomato seedling production systems, the treatment with the highest relative growth rate differed from the treatment with the highest compactness and DQI, and treatment responses also varied among root traits [10]. Such results illustrate that individual indicators describe different dimensions of seedling status. A multitrait assessment therefore also requires a way to account for differences in the relative importance of the component traits.

A multitrait scoring system requires both a quantitative representation of trait importance and a common scale for measurements that differ in units and magnitude. The analytic hierarchy process (AHP) is a multicriteria decision-making approach in which pairwise comparisons are used to express expert priorities as ratio-scale weights [13–15]. For group AHP, individual judgments can be combined into a group comparison matrix, commonly using geometric means for each pairwise comparison [16, 17]. Z-score standardization places measurements with different units on a common dimensionless scale [18, 19], but a high or low z-score does not by itself indicate superior seedling quality. For many seedling traits, values that are either too low or too high may be undesirable. A practical scoring framework therefore needs to integrate standardized position, crop-specific target ranges, and trait importance. Field-oriented studies that combine these components into crop-specific multitrait scores remain limited.

The objectives of this study were to (1) select crop-specific traits for assessing seedling quality in pepper, tomato, watermelon, kimchi cabbage, and cucumber; (2) derive trait weights from expert pairwise comparisons using AHP; (3) establish stepwise standard-score intervals from expert-defined target ranges and measured seedling data; and (4) combine trait weights and standard scores into crop-specific 0–100 assessment systems. The calculation procedure and interpretation were further illustrated using independent example seedlings that were not used to derive the weights or scoring intervals.

Methods

Target crops and selection of assessment traits

Crop-specific seedling quality assessment systems were developed for pepper, tomato, watermelon, kimchi cabbage, and cucumber, which are major crops in the Korean commercial nursery industry [20] (Table 1). Fruiting and leafy vegetables were included to compare common and crop-specific assessment requirements across contrasting growth habits and production objectives.

Table 1
Seedling production volumes and sales values for major vegetable crops in Korea in 2022.

Crop	Sales value (10^4 KRW)	Production volume (10^4 seedlings)	Crop	Sales value (10^4 KRW)	Production volume (10^4 seedlings)
Pepper	4640272	15758	Lettuce	881323	5686
Tomato	2670203	4856	Pumpkin	438592	1119
Cucumber	2047206	4119	Onion	364859	8867
Watermelon	1747146	3511	Eggplant	295981	645
Kimchi cabbage	1298660	16673	Melon	217826	486
Data source: Korea Seed & Variety Service [20].					
Crops are listed in descending order of sales value.					

Assessment traits were selected in two stages. Candidate traits were compiled from previous seedling studies and indicators used in commercial nursery production. Each candidate was then evaluated for biological relevance, feasibility of measurement or visual assessment, and applicability under commercial nursery conditions. The final trait sets were determined after consultation with nursery growers.

Expert survey and derivation of AHP weights

Pairwise-comparison surveys were conducted with nursery professionals to quantify the relative importance of the final assessment traits for each crop. Participants were purposively selected based on their experience in crop-specific seedling production and in nursery management or production control. Surveys were conducted from 2022 to 2024. Respondent characteristics are summarized in Tables 2–3. The final analysis included 19–26 respondents per crop; mean age ranged from 49.6 to 50.9 years and mean professional experience from 17.7 to 18.7 years. When one professional responded for more than one crop, the judgments for each crop were treated as separate crop-specific responses.

Table 2
Demographic characteristics of respondents.

Crop	Age (years)[z]			Experience (years)[z]			Respondents (no.)
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	
Pepper	50.9	29	65	18.5	2	31	26
Tomato	50.2	29	65	17.7	2	31	24
Watermelon	50.2	32	65	17.9	2	31	20
Kimchi cabbage	49.6	29	65	18.2	2	31	23
Cucumber	50.9	32	65	18.7	8	31	19

[z] Age and professional experience are based on the year in which each response was collected.

Table 3
Distribution of respondents by academic major (%).

Academic major	Pepper	Tomato	Watermelon	Kimchi cabbage	Cucumber
Horticulture	38.5	45.8	45.0	39.1	42.1
Agronomy	19.2	20.8	20.0	13.0	21.1
Other	19.2	12.5	15.0	26.1	15.8
No response	23.1	20.8	20.0	21.7	21.1
Total	100.0	100.0	100.0	100.0	100.0

The AHP procedure followed the standard sequence of pairwise scaling, comparison-matrix construction, eigenvalue-based weighting, and consistency assessment [13–15]. All pairwise combinations of the selected traits were evaluated on a nine-point scale. A value of 1 indicated equal importance, whereas values from 2 to 9 represented increasing preference for one trait over the other. Respondents first ranked the complete set of traits and then used that ranking as a reference when making each pairwise judgment. For each respondent, the pairwise comparison matrix was denoted as $A = (a_{ij})$, where a_{ij} represents the importance of trait i relative to trait j. Relative weights were obtained from the principal-eigenvalue relationship:

$$Aw = \lambda_{max} w, \Sigma_{i=1}^{n} w_i = 1$$

where $w = (w_1, w_2, \ldots, w_n)$ is the vector of relative trait weights, w_i is the normalized weight of trait i, λ_{max} is the maximum eigenvalue of the pairwise comparison matrix, and n is the number of assessment traits.

Logical consistency of each response was evaluated using the consistency index (CI) and consistency ratio (CR) [13, 14]:

$CI = (\lambda_{max} - n)/(n - 1)$

$$CR = CI/RI$$

where RI is the random index corresponding to matrix order n and represents the mean consistency index obtained from random reciprocal matrices of the same order.

A CR of 0.10 or less is commonly regarded as acceptable in AHP [13–15], although thresholds up to 0.20 have been proposed for larger comparison matrices [21]. Respondents reviewed trait pairs that were inconsistent with their initial overall ranking and either retained or revised the comparison according to their final judgment. The researchers did not suggest replacement values. Only responses with CR < 0.20 after review were retained for the final analysis.

The reviewed individual matrices were aggregated at the group level. For each crop, a group comparison matrix was constructed from the geometric mean of the respondent-specific values for each pairwise comparison [16]:

$\bar{a}_{ij} = (\prod_{r=1}^{R} a_{ij}^{(r)})^{1/R}$

where $\bar{a}_{ij}$ is the aggregated comparison value between traits i and j, $a_{ij}^{(r)}$ is the corresponding judgment of respondent r, and R is the number of valid respondents for that crop. The eigenvalue method was then applied to each crop-level group matrix to obtain the final weight vector.

Survey of target ranges and construction of standard-score intervals

For quantitative seedling traits, movement in one direction does not necessarily indicate improved quality, and the appropriate range may differ by crop and trait. For example, among 15- to 42-day-old tomato seedlings of ‘Solan Vajr’, fruit and seed yields were highest for 33-day-old transplants, demonstrating that the effect of seedling age was not simply monotonic [22]. Because the appropriate level of an individual trait can also depend on other seedling attributes, nursery environment, and post-transplant production conditions, its relationship with productivity cannot be generalized to a single biological optimum. The ranges used here were therefore intended as initial, field-oriented target ranges derived from expert judgment rather than as biologically optimal ranges validated against post-transplant performance.

The same experts were also surveyed from 2022 to 2024 to specify ranges they considered appropriate for commercial plug seedlings. Respondents were instructed to (1) consider plug seedlings, (2) disregard individual cultivars, (3) apply their own general nursery criteria rather than the requirements of

a particular customer, (4) use either grafted or non-grafted seedlings according to the type that accounted for the larger share of production in their nursery, and (5) distinguish among seasons. To reduce variation associated with market type and production purpose, crop types were restricted as follows: pepper, to market types used for dried red pepper production or harvested green for fresh consumption; tomato, to standard large-fruited types; watermelon, to large-fruited types; and kimchi cabbage, to heading types. For cucumber, the major white-spined and green-spined cultivar groups were pooled because preliminary consultation indicated that their assessment criteria were similar. Review of responses by grafting status and season showed no clear differences for most traits other than seedling age, and the number of respondents allowing direct grafted-versus-non-grafted comparison was limited. Responses across grafting status and season were therefore pooled when deriving the final target ranges.

The lower and upper limits reported by experts were treated as boundary judgments defining individual target ranges and were pooled for analysis. When a respondent provided multiple ranges according to grafting status or season, the boundary values were weighted so that each expert contributed equally overall. Rather than estimating separate representative lower and upper limits, the approach was designed to capture the central distribution of the boundary judgments. The first and third quartiles of the adjusted pooled boundary-value distribution were therefore used as the lower and upper limits of the initial target range, respectively. A separate calculation based on lower and upper distributions was also examined; for several traits with overlapping boundary distributions, this produced identical or nearly identical group limits and consequently a zero or excessively narrow target range. For leaf color, respondents could select multiple acceptable examples, and every color chosen by at least one respondent was retained in the crop-specific acceptable set. Leaf area was excluded from the target-range survey because numerical target limits could not be specified using this survey approach. Disease and pest status and uniformity were excluded from the range survey because both were treated as directional traits, with absence of visible disease/pest problems and greater uniformity considered preferable.

Standard-score intervals were constructed in three steps. First, quantitative traits other than uniformity were standardized as z-scores. Second, the target and overall range boundaries were defined. Third, values outside the target range were divided into penalty intervals. Z-scores were calculated as follows [18, 19]:

$$z = (X - \mu)/\sigma$$

where X is the observed value, μ is the trait mean, and σ is the standard deviation. Means and standard deviations used for standardization were primarily calculated from seedling measurements collected from 2022 to 2024 (Table 4).

Table 4
Sample sizes and seedling ages of measured seedling datasets.

Crop	Samples (no.)	Days after sowing (days)
Pepper	85	55.8 ± 8.4[z]
Tomato	149	41.3 ± 6.8
Watermelon	282	32.9 ± 3.7
Kimchi cabbage	309	25.1 ± 4.1
Cucumber	214	23.4 ± 3.1

[z] Values are presented as mean ± standard deviation.

For pepper and tomato, plant height was measured from the substrate surface to the shoot apex. Stem diameter was measured 1 cm above the substrate surface using a digital caliper (CD-20APX, Mitutoyo Co., Ltd., Kanagawa, Japan). True leaves shorter than 2 cm were excluded from leaf-number and leaf-area determinations, and leaf area was quantified using ImageJ (National Institutes of Health, Bethesda, MD, USA).

For watermelon and cucumber, plant height was measured from the substrate surface to the shoot apex, and stem diameter was measured 1 cm above the substrate surface using the same digital caliper model. Only true leaves at least 1 cm long were counted. Node number was determined by counting nodes bearing true leaves. Individual-plant leaf area was calculated as the sum of cotyledon and true-leaf areas measured separately with a leaf-area meter (LI-3100C Area Meter, LI-COR Inc., Lincoln, NE, USA).

For kimchi cabbage, leaf length was measured from the leaf base to the tip of the longest leaf on each plant. Only expanded true leaves at least 0.8 cm long were counted. Leaf area was measured for each true leaf using a leaf-area meter (LI-3100 Area Meter, LI-COR Inc., Lincoln, NE, USA) and summed at the plant level. Seedling age for all crops was calculated as days from sowing to measurement.

Because some traits contained missing values, the number of observations used for standardization was smaller than the total crop-specific sample size for those traits; trait-specific sample sizes are reported in Tables 8–12. The lower and upper target-range limits on the original scale are denoted K_{min} and K_{max}, and their standardized values as z_{min} and z_{max}.

Alternative data sources were used when measured datasets were unavailable or when the survey did not provide a numerical target range. For node number and the first flower node in pepper, node number and the first inflorescence node in tomato, and leaf width in kimchi cabbage, no measured dataset was available. Means and standard deviations were therefore calculated from survey boundary values after adjustment for equal respondent contribution; the first and third quartiles for these traits were obtained

from the same boundary-value distributions. For leaf area, the first and third quartiles of the measured distribution were used as the lower and upper target limits, respectively.

The overall scoring range was defined primarily by the minimum and maximum values in the measured dataset. If an expert-derived target boundary extended beyond the measured range, the corresponding overall boundary was expanded to include the survey value; in practice, this adjustment was required only for upper limits. For pepper and tomato node number and kimchi cabbage leaf width, which lacked measured datasets, the minimum and maximum survey responses defined the overall range. Survey values were also used to define the standardization basis and target range for the first flower node in pepper and the first inflorescence node in tomato. Seedlings in which the first flower or inflorescence had not emerged were classified as non-emerged and assigned a score of 0. For emerged flowers or inflorescences, the survey minimum and maximum defined the overall range, and scores decreased with increasing distance from the target range.

Distances below and above the target range were each divided into five equal-width penalty intervals. This produced a common six-level scoring scheme of 1.0, 0.8, 0.6, 0.4, 0.2, and 0 for all quantitative traits. Values within the target range received 1.0, and the score decreased by 0.2 for each interval farther from the target range. Values outside the overall range received 0. When the target range was not centered within the overall range, the lower- and upper-side penalty intervals consequently differed in width.

The basic assessment unit was an individual seedling. Uniformity, however, was defined as a group-level attribute describing variation among plants within the tray or production lot to which the seedling belonged. Plant height was measured for each seedling sampled from that production unit. The coefficient of variation was then calculated, and the same uniformity value was assigned to seedlings belonging to that sampled group.

The uniformity index was defined as 1 minus the coefficient of variation in plant height, where the coefficient of variation was calculated as the standard deviation divided by the mean. Because the resulting index was already dimensionless on a nominal 0–1 scale and larger values indicated greater uniformity, it was not z-standardized. The 0–1 scale was divided into six intervals receiving direct standard scores of 1.0, 0.8, 0.6, 0.4, 0.2, and 0. Uniformity-index values below 0, if encountered theoretically, were set to 0.

For qualitative traits, leaf color was scored 1 when it matched any crop-specific acceptable color and 0 otherwise. Disease and pest status was scored 1 when no visible disease or pest symptoms were observed and 0 when such symptoms were present.

Weighted composite seedling quality score

For each crop, the composite score Q was calculated as the weighted sum of the standard scores for all assessment traits:

$Q = \Sigma_{i=1}^{n} w_i s_i$

where w_i is the AHP weight of trait i and s_i is its standard score. Because the weights sum to 1 within each crop, Q ranges from 0 to 1. For ease of interpretation, Q was multiplied by 100 and reported on a 0–100 scale. Figure 1 summarizes the parallel derivation of trait weights and standard-score intervals and their subsequent combination in the weighted sum.

Application of the assessment system and comparison with growth-related indices

To illustrate the calculation procedure, example seedlings were selected from independent nursery experiments that were not used to derive the trait weights or scoring intervals. Production information and the input measurements for the pepper growth-related indices are provided in Additional file 1. Plant height, stem diameter, leaf number, leaf area, and other individual traits were measured directly on each example seedling. Uniformity was calculated from the plant-height coefficient of variation of 10 plants from the group to which each example seedling belonged; pepper seedlings A and B were assigned values from two different 10-plant groups. Thus, individual traits represent measurements of the focal seedling, whereas uniformity represents a group-level value shared by seedlings in the corresponding production unit.

For the two pepper seedlings, whole-seedling dry matter content (DM) and the height-to-stem-diameter ratio were examined alongside the composite score. DM was calculated as whole-seedling dry mass divided by whole-seedling fresh mass × 100. The height-to-stem-diameter ratio was calculated as plant height (cm) divided by stem diameter (mm). The input measurements and calculation formulas are provided in Additional file 1. These derived indices were not included as additional terms in the composite-score calculation and were used only to describe the two example seedlings.

AI-assisted manuscript preparation

ChatGPT (OpenAI) was used to assist with English translation, language editing, and manuscript formatting. The authors reviewed the translated and edited text, verified the scientific content and references, and remain fully responsible for the final manuscript.

Results

Crop-specific assessment traits

The candidate pool included leaf number, leaf color, leaf area, disease and pest status, seedling age, and uniformity across several crops. Candidate traits for fruiting vegetables also included plant height, stem diameter, and developmental traits associated with plant architecture and reproductive stage, whereas kimchi cabbage candidates included leaf length and leaf width as indicators of leaf expansion (Table 5).

Table 5
Candidate traits for seedling quality assessment by crop.

Pepper	Tomato	Watermelon	Kimchi cabbage	Cucumber
Plant height	Plant height	Plant height	Leaf length	Plant height
Internode length	Internode length	Internode length	Leaf width	Internode length
Stem diameter	Stem diameter	Stem diameter	Plant height	Stem diameter
Number of leaves	Number of leaves	Number of leaves	Canopy width	Number of leaves
Leaf color	Leaf color	Leaf color	Number of leaves	Leaf color
Leaf area	Leaf area	Leaf area	Leaf color	Leaf area
Chlorophyll content	Chlorophyll content	Chlorophyll content	Leaf area	Chlorophyll content
Fresh weight	Fresh weight	Fresh weight	Chlorophyll content	Fresh weight
Disease and pest status	Disease and pest status	Disease and pest status	Fresh weight	Disease and pest status
Seedling age	Seedling age	Seedling age	Disease and pest status	Seedling age
First flower node	Chlorophyll fluorescence	Uniformity	Seedling age	Uniformity
Uniformity	First inflorescence node	Cotyledon thickness	Uniformity	Hypocotyl length
	Uniformity	Cotyledon area		Number of flowers
		Number of flowers		

The final systems contained 10 traits each for pepper and tomato: plant height, node number, stem diameter, leaf number, leaf color, leaf area, disease and pest status, seedling age, first flower node in pepper or first inflorescence node in tomato, and uniformity. Watermelon and cucumber each contained nine traits, excluding the reproductive-node trait, whereas kimchi cabbage contained eight traits: leaf length, leaf width, leaf number, leaf color, leaf area, disease and pest status, seedling age, and uniformity (Table 6).

Table 6
Final traits selected for seedling quality assessment by crop.

Pepper	Tomato	Watermelon	Kimchi cabbage	Cucumber
Plant height	Plant height	Plant height	Leaf length	Plant height
Number of nodes	Number of nodes	Number of nodes	Leaf width	Number of nodes
Stem diameter	Stem diameter	Stem diameter	Number of leaves	Stem diameter
Number of leaves	Number of leaves	Number of leaves	Leaf color	Number of leaves
Leaf color	Leaf color	Leaf color	Leaf area	Leaf color
Leaf area	Leaf area	Leaf area	Disease and pest status	Leaf area
Disease and pest status	Disease and pest status	Disease and pest status	Seedling age	Disease and pest status
Seedling age	Seedling age	Seedling age	Uniformity	Seedling age
First flower node	First inflorescence node	Uniformity		Uniformity
Uniformity	Uniformity			

Plant height, node number, stem diameter, leaf number, leaf length, leaf width, leaf area, seedling age, first flower/inflorescence node, and uniformity were treated as quantitative traits and scored according to numerical measurements. Leaf color and disease and pest status were treated as qualitative traits and scored using predefined criteria.

AHP weights and consistency

The final CR values of the crop-level group matrices ranged from 0.0061 to 0.0720 and were below 0.10 for all crops (Table 7).

Table 7
Relative importance of seedling quality traits by crop.

Trait	Pepper	Tomato	Watermelon	Kimchi cabbage	Cucumber
Plant height	0.0984	0.0937	0.0914	NA[z]	0.0922
Number of nodes	0.0582	0.0670	0.0607	NA	0.0608
Stem diameter	0.0595	0.0574	0.0685	NA	0.0673
Number of leaves	0.0521	0.0409	0.0468	0.1270	0.0491
Leaf color	0.0461	0.0400	0.0394	0.0486	0.0401
Leaf area	0.0312	0.0298	0.0355	0.0531	0.0367
Disease and pest status	0.2871	0.2842	0.3490	0.3422	0.3376
Seedling age	0.1158	0.1036	0.1029	0.1276	0.1119
First flower/inflorescence node	0.0711	0.0827	NA	NA	NA
Uniformity	0.1805	0.2006	0.2058	0.1979	0.2043
Leaf length	NA	NA	NA	0.0497	NA
Leaf width	NA	NA	NA	0.0538	NA
n	26	24	20	23	19
CR	0.0125	0.0720	0.0112	0.0061	0.0107

[z] NA, not applicable because the trait was not selected for the corresponding crop; therefore, no weight was calculated. n, number of valid responses included in the final AHP analysis; CR, consistency ratio.

Disease and pest status received the largest weight in every crop: 0.2871 in pepper, 0.2842 in tomato, 0.3490 in watermelon, 0.3422 in kimchi cabbage, and 0.3376 in cucumber. Uniformity weights were 0.1805, 0.2006, 0.2058, 0.1979, and 0.2043, respectively, and seedling-age weights were 0.1158, 0.1036, 0.1029, 0.1276, and 0.1119. Crop-specific traits included the first flower node in pepper (0.0711), the first inflorescence node in tomato (0.0827), and leaf length (0.0497) and leaf width (0.0538) in kimchi cabbage (Table 7).

Crop-specific standard-score intervals

Quantitative traits received a score of 1.0 within the target range, with scores declining to 0.8, 0.6, 0.4, 0.2, and 0 as values moved progressively farther from either boundary. Bidirectional penalties were used for traits such as plant height, stem diameter, leaf number, leaf area, and seedling age. Uniformity was not converted to a z-score; instead, its original 0–1 scale was divided into six intervals in which larger

values received higher scores. Leaf color and disease and pest status were excluded from the quantitative interval tables because each was scored directly as 0 or 1.

Tables 8–12 report, by crop, the mean and standard deviation of quantitative traits, target and overall ranges on both the original and z-score scales, and the number of measured observations used for standardization. Uniformity is shown only on its original scale. Complete score intervals for the 1.0–0 categories are provided in Appendix Tables 1–5.

Table 8
Scoring criteria for pepper seedling quality traits.

Trait (unit)	Mean	SD[z]	Original scale		z-score scale		n
			Target	Overall	Target	Overall	
Plant height (cm)	21.9	7.8	25.0–32.0	9.3–40.0	0.4–1.3	−1.6–2.3	45
Number of nodes (no.)	9.5	2.8	8.0–12.0	3.0–15.0	−0.5–0.9	−2.3–2.0	–
Stem diameter (mm)	3.6	0.7	3.8–5.0	2.0–15.0	0.2–2.0	−2.3–16.2	44
Number of leaves (no.)	12.2	6.0	8.0–12.0	6.0–31.0	−0.7–−0.0	−1.0–3.2	45
Leaf area (cm²)	137.0	77.9	93.7–152.1	30.9–355.1	−0.6–0.2	−1.4–2.8	45
Seedling age (days)	55.8	8.4	55.0–80.0	40.0–100.0	−0.1–2.9	−1.9–5.2	85
First flower node (no.)	9.3	2.9	8.0–11.3	3.0–13.0	−0.5–0.7	−2.2–1.3	–
Uniformity (index)	–	–	0.83–1.00	0.00–1.00	–	–	–

[z] SD, standard deviation. n, number of observations in the measured dataset used for standardization; –, not applicable because the trait was based on expert survey data or direct scoring. Uniformity was scored directly on its original 0–1 scale and was not z-standardized. A seedling without a visible first flower was assigned a score of 0 and was not included in the overall range for this trait.

Table 9
Scoring criteria for tomato seedling quality traits.

Trait (unit)	Mean	SD[z]	Original scale		z-score scale		n
			Target	Overall	Target	Overall	
Plant height (cm)	18.2	9.3	25.0–30.0	3.7–40.0	0.7–1.3	−1.6–2.3	149
Number of nodes (no.)	7.3	2.0	6.0–9.0	4.0–13.0	−0.7–0.8	−1.6–2.8	–
Stem diameter (mm)	3.8	0.8	4.0–7.0	3.0–15.0	0.2–4.0	−1.0–13.9	149
Number of leaves (no.)	5.8	1.4	6.0–8.0	3.0–16.0	0.1–1.5	−2.0–7.2	144
Leaf area (cm²)	104.6	57.4	54.5–147.9	10.0–251.9	−0.9–0.8	−1.6–2.6	144
Seedling age (days)	41.3	6.8	44.3–55.0	25.0–75.0	0.4–2.0	−2.4–5.0	149
First inflorescence node (no.)	6.9	1.8	6.0–8.0	3.0–11.0	−0.5–0.6	−2.2–2.3	–
Uniformity (index)	–	–	0.83–1.00	0.00–1.00	–	–	–

[z] SD, standard deviation. n, number of observations in the measured dataset used for standardization; –, not applicable because the trait was based on expert survey data or direct scoring. Uniformity was scored directly on its original 0–1 scale and was not z-standardized. A seedling without a visible first inflorescence was assigned a score of 0 and was not included in the overall range for this trait.

Table 10
Scoring criteria for watermelon seedling quality traits.

Trait (unit)	Mean	SD[z]	Original scale		z-score scale		n
			Target	Overall	Target	Overall	
Plant height (cm)	19.2	10.5	20.0–25.0	4.0–55.2	0.1–0.6	−1.4–3.4	238
Number of nodes (no.)	6.1	1.7	4.0–5.0	2.0–11.0	−1.2–−0.6	−2.3–2.8	281
Stem diameter (mm)	5.4	0.8	5.0–10.0	3.0–15.0	−0.5–5.6	−2.9–11.6	282
Number of leaves (no.)	6.7	1.6	4.0–6.0	2.0–13.0	−1.7–−0.5	−3.0–4.0	238
Leaf area (cm²)	120.6	29.5	102.2–142.7	49.2–180.5	−0.6–0.7	−2.4–2.0	110
Seedling age (days)	32.9	3.7	35.0–50.0	25.0–65.0	0.6–4.6	−2.1–8.6	282
Uniformity (index)	–	–	0.83–1.00	0.00–1.00	–	–	–

[z] SD, standard deviation. n, number of observations in the measured dataset used for standardization; –, not applicable because uniformity was scored directly on its original 0–1 scale without z-score standardization.

Table 11
Scoring criteria for kimchi cabbage seedling quality traits.

Trait (unit)	Mean	SD[z]	Original scale		z-score scale		n
			Target	Overall	Target	Overall	
Leaf length (cm)	9.8	3.4	5.0–8.0	3.0–20.0	−1.4–−0.5	−2.0–3.0	309
Leaf width (cm)	3.2	1.5	2.0–4.0	1.0–8.0	−0.8–0.5	−1.5–3.2	–
Number of leaves (no.)	5.2	1.2	5.0–8.0	3.0–9.0	−0.2–2.3	−1.9–3.1	309
Leaf area (cm²)	60.8	39.8	31.9–75.0	7.3–194.4	−0.7–0.4	−1.3–3.4	309
Seedling age (days)	25.1	4.1	24.0–30.0	20.0–40.0	−0.3–1.2	−1.2–3.7	309
Uniformity (index)	–	–	0.83–1.00	0.00–1.00	–	–	–

[z] SD, standard deviation. n, number of observations in the measured dataset used for standardization; –, not applicable because the trait was based on expert survey data or direct scoring. Uniformity was scored directly on its original 0–1 scale and was not z-standardized.

Table 12
Scoring criteria for cucumber seedling quality traits.

Trait (unit)	Mean	SD[z]	Original scale		z-score scale		n
			Target	Overall	Target	Overall	
Plant height (cm)	9.7	5.7	15.0–20.0	3.5–28.0	0.9–1.8	−1.1–3.2	111
Number of nodes (no.)	3.3	0.8	3.0–5.0	1.0–6.0	−0.4–2.1	−2.9–3.4	214
Stem diameter (mm)	4.3	0.5	5.0–8.0	3.2–15.0	1.4–7.8	−2.6–22.7	213
Number of leaves (no.)	3.8	1.3	3.0–4.3	1.0–7.0	−0.6–0.4	−2.2–2.5	111
Leaf area (cm²)	84.9	29.8	63.5–109.0	31.3–172.8	−0.7–0.8	−1.8–3.0	111
Seedling age (days)	23.4	3.1	25.0–35.0	20.0–45.0	0.5–3.7	−1.1–7.0	214
Uniformity (index)	–	–	0.83–1.00	0.00–1.00	–	–	–

[z] SD, standard deviation. n, number of observations in the measured dataset used for standardization; –, not applicable because uniformity was scored directly on its original 0–1 scale without z-score standardization.

Most respondents based their evaluations on grafted seedlings, whereas only a few provided responses for non-grafted seedlings. Among the limited comparable responses, trait ranges were generally similar except for seedling age, which tended to be longer for grafted seedlings. Across seasonal responses from the same experts, plant height, node number, stem diameter, leaf number, and the first flower/inflorescence node showed no clear seasonal shift, whereas seedling age tended to be longer in winter.

For leaf color, every example selected as acceptable by at least one expert was retained; no minimum selection-frequency threshold was imposed. Crop-specific acceptable colors are shown in Fig. 2, and summary CIE L*a*b* coordinates converted from the corresponding red–green–blue (RGB) values are reported in Additional file 2. A seedling received 1 for leaf color when its color matched the acceptable set and 0 otherwise.

The two scoring structures are illustrated using pepper plant height and uniformity (Fig. 3). Plant height received 1.0 between z = 0.4 and 1.3 and lower scores at increasing distances on either side. Uniformity received 1.0 on the original scale from 0.83 to 1.00, with scores decreasing sequentially to 0.8, 0.6, 0.4, 0.2, and 0 as uniformity declined.

Weighted composite assessment system

For all crops, the final score was calculated as $100 \times \Sigma w_i s_i$. Although the trait sets, weights, and target ranges differed among crops, weights summed to 1 and trait scores were expressed on a 0–1 scale. The same computational structure could therefore be applied across crops while retaining crop-specific parameter values.

Application to example seedlings

When the assessment systems were applied to independent example seedlings, pepper seedlings A and B received composite scores of 85.9 and 75.5, respectively (Table 13). Scores for the tomato, watermelon, kimchi cabbage, and cucumber examples were 87.2, 85.8, 90.7, and 85.3, respectively (Table 14).

Table 13
Trait scores and weighted results for two example pepper seedlings.

Trait (unit)	Seedling A		Seedling B		Weight
	Measured value	Standard score	Measured value	Standard score	
Plant height (cm)	31.3	1.0	48.9	0.0	0.0984
Number of nodes (no.)	8.0	1.0	12.0	1.0	0.0582
Stem diameter (mm)	3.2	0.6	4.5	1.0	0.0595
Number of leaves (no.)	12.0	1.0	15.0	0.8	0.0521
Leaf color (binary)	1.0	1.0	1.0	1.0	0.0461
Leaf area (cm^2)	117.8	1.0	240.8	0.4	0.0312
Disease and pest status (binary)	1.0	1.0	1.0	1.0	0.2871
Seedling age (days)	51.0	0.6	51.0	0.6	0.1158
First flower node (no.)	Not emerged	0.0	Not emerged	0.0	0.0711
Uniformity (index)	0.96	1.0	0.97	1.0	0.1805
Total score (100-point scale)	85.9		75.5		-

Stem diameters are displayed to one decimal place. Trait scores and composite scores were calculated from the original, unrounded measurements.

Table 14
Assessment results for example tomato, watermelon, kimchi cabbage, and cucumber seedlings.

Crop	Trait (unit)	Measured value	Standard score	Weight	Total score (100-point scale)
Tomato	Plant height (cm)	33.4	0.6	0.0937	87.2
	Number of nodes (no.)	7.0	1.0	0.0670	
	Stem diameter (mm)	5.8	1.0	0.0574	
	Number of leaves (no.)	8.0	1.0	0.0409	
	Leaf color (binary)	0.0	0.0	0.0400	
	Leaf area (cm²)	242.9	0.0	0.0298	
	Disease and pest status (binary)	1.0	1.0	0.2842	
	Seedling age (days)	43.0	0.8	0.1036	
	First inflorescence node (no.)	7.0	1.0	0.0827	
	Uniformity (index)	0.88	1.0	0.2006	
Watermelon	Plant height (cm)	14.1	0.6	0.0914	85.8
	Number of nodes (no.)	3.0	0.4	0.0607	
	Stem diameter (mm)	5.3	1.0	0.0685	
	Number of leaves (no.)	4.0	1.0	0.0468	
	Leaf color (binary)	1.0	1.0	0.0394	
	Leaf area (cm²)	96.7	0.8	0.0355	
	Disease and pest status (binary)	1.0	1.0	0.3490	
	Seedling age (days)	30.0	0.4	0.1029	
	Uniformity (index)	0.91	1.0	0.2058	
Kimchi cabbage	Leaf length (cm)	8.9	0.8	0.0497	90.7
	Leaf width (cm)	4.2	0.8	0.0538	

Stem diameters are displayed to one decimal place. Trait scores and composite scores were calculated from the original, unrounded measurements.

Crop	Trait (unit)	Measured value	Standard score	Weight	Total score (100-point scale)
	Number of leaves (no.)	7.0	1.0	0.1270	
	Leaf color (binary)	1.0	1.0	0.0486	
	Leaf area (cm²)	110.6	0.6	0.0531	
	Disease and pest status (binary)	1.0	1.0	0.3422	
	Seedling age (days)	23.0	0.6	0.1276	
	Uniformity (index)	0.92	1.0	0.1979	
Cucumber	Plant height (cm)	14.2	0.8	0.0922	85.3
	Number of nodes (no.)	2.0	0.4	0.0608	
	Stem diameter (mm)	4.1	0.4	0.0673	
	Number of leaves (no.)	3.0	1.0	0.0491	
	Leaf color (binary)	1.0	1.0	0.0401	
	Leaf area (cm²)	148.2	0.2	0.0367	
	Disease and pest status (binary)	1.0	1.0	0.3376	
	Seedling age (days)	24.0	0.8	0.1119	
	Uniformity (index)	0.90	1.0	0.2043	

Stem diameters are displayed to one decimal place. Trait scores and composite scores were calculated from the original, unrounded measurements.

Pepper seedling A received 1.0 for plant height, node number, leaf number, leaf color, leaf area, disease and pest status, and uniformity; 0.6 for stem diameter and seedling age; and 0 for the first flower node, giving a composite score of 85.9 (Table 13). Seedling B received 0 for plant height because the measurement exceeded the overall range, and lower scores for leaf number (0.8) and leaf area (0.4), resulting in a total of 75.5. The two seedlings received identical scores for node number, leaf color, disease and pest status, seedling age, first flower node, and uniformity. Although seedling B received a higher stem-diameter score, seedling A had higher scores for plant height, leaf number, and leaf area, producing the higher composite score.

The tomato example received 0 for leaf color and leaf area, 0.6 for plant height, 0.8 for seedling age, and 1.0 for all remaining traits, resulting in a composite score of 87.2 (Table 14).

Pepper seedling A had a higher whole-seedling dry matter content (DM; 14.9% vs. 12.2%) and a lower height-to-stem-diameter ratio (9.84 vs. 10.89 cm mm^{-1}) than seedling B (Table 15).

Table 15
Comparison of growth-related indices for two example pepper seedlings.

Seedling	DM (%)	Height-to-stem-diameter ratio (cm mm^{-1})
A	14.9	9.84
B	12.2	10.89

DM, whole-seedling dry matter content, calculated as whole-seedling dry mass / whole-seedling fresh mass × 100. Height-to-stem-diameter ratio = plant height (cm) / stem diameter (mm). Input measurements and formulas are provided in Additional file 1. Values describe individual seedlings, not treatment means.

Discussion

This study integrated expert-derived weights and crop-specific target ranges for seedling traits that differ in units and biological meaning, producing a single composite score for each crop. Application to independent example seedlings showed that the same computational procedure could be used across five crops, but it did not establish reproducibility across production environments or predictive validity for post-transplant performance. Previous studies likewise show that the extent to which pre-transplant differences persist after transplanting varies with crop and nursery conditions, and that some early differences diminish as plants develop [5, 8–10, 23]. The proposed systems should therefore be interpreted as tools for summarizing the status of multiple traits against crop-specific criteria rather than as absolute definitions of seedling quality.

Differences among the final trait sets reflect crop-specific growth habit and production goals. In pepper, the first flower node provides information on reproductive development and has been used in relation to flowering time and fruit earliness [24]. In tomato, the number of leaves below the first inflorescence and the time to anthesis of the first flower in the first inflorescence respond to nursery temperature and root-zone volume [25, 26], indicating that the position and development of the first inflorescence are sensitive to nursery conditions. Because the present study did not test whether the first flower node in pepper or the first inflorescence node in tomato predicts subsequent flowering, fruit set, or harvest timing, these traits should be interpreted here only as crop-specific indicators of reproductive developmental stage. In kimchi cabbage, leaf length and leaf width were retained as descriptors of leaf expansion and shoot development. These differences support the use of a core set of common traits together with crop-specific traits.

Disease and pest status received the largest weight in every crop, while uniformity and seedling age also ranked highly. This pattern indicates that experts considered plant health, within-lot consistency, and appropriate shipping stage in addition to seedling size. Disease and pest problems can directly

compromise transplant survival and subsequent productivity. For example, broccoli and cabbage transplants with severe wirestem caused by *Rhizoctonia solani* had lower post-transplant survival and a lower proportion of marketable heads than healthy transplants [27]. Uniformity describes variation among plants within a production unit rather than the size of an individual seedling and is a major quality-control concern in commercial nurseries [11]. Seedling age is also linked to transplant timing, and its relationship with post-transplant growth and yield varies among crops and production conditions [3, 8, 22, 28]. Importantly, AHP weights are not coefficients of causal effects on post-transplant growth or yield; they represent expert-assigned relative priorities within the specified assessment objective and trait set [13–15]. Thus, a larger weight for disease and pest status than for plant height should be interpreted as relative priority within the expert judgment framework, not as evidence of a larger causal effect.

Disease and pest status was scored dichotomously and carried a weight of 0.2842–0.3490 (Table 7). If all other trait scores are held constant, changing this score from 1 to 0 lowers the composite score by 28.4–34.9 points, depending on crop. Even when every other trait receives its maximum score, the theoretical upper limit for a seedling with visible disease or pest problems is therefore only 65.1–71.6. Disease or pest occurrence is thus strongly penalized under the current weighted-sum formulation. These values should not, however, be treated as empirical thresholds for shipment suitability. Future comparisons between actual commercial acceptance decisions and composite scores are needed to determine whether disease and pest status should remain a weighted trait or instead operate as an exclusion criterion.

Interpretation of the weights should also account for consistency of the group matrix and dependence on the sampled expert population. Geometric aggregation of pairwise judgments preserves the reciprocal structure required for construction of a group comparison matrix [16, 17]. Crop-level group matrices in this study had CR values of 0.0061–0.0720, indicating high logical consistency among the aggregated pairwise judgments. This does not imply agreement among individual experts, establish biological validity of the selected traits, or guarantee that the same weights would be reproduced in another expert panel. Weight estimates may change with respondent composition, regional representation, sample size, or survey timing; replication with independent expert groups and resampling-based stability analyses would therefore be informative.

A low weight does not imply that an assessment trait is unnecessary. AHP weights express relative proportions within a defined hierarchy, and both their magnitude and rank can change when the set or structure of criteria changes. Consequently, weights for the same trait should be interpreted within the crop-specific trait set rather than compared as absolute measures of importance across crops.

The composite score combines these weights with trait-level standard scores. Quantitative traits other than uniformity were standardized and then converted to stepwise scores according to distance from the target range; uniformity was scored directly on its original 0–1 scale, and qualitative traits received binary scores according to predefined criteria. Standardization was used to place measurements with

different units on a common scale, not to equate larger z-scores with better seedlings. Likewise, the 0.2 increments between score classes are computational penalties and do not imply equally spaced biological responses after transplanting.

Wu et al. [29] summed z-scores for multiple morphological and mechanical traits to compare overall growth responses to light-quality treatments. Direct aggregation of standardized values is useful when larger values are intended to contribute positively to a composite response, but it is less suitable for traits for which both low and high extremes may be undesirable unless directionality is explicitly adjusted. In the present framework, z-scores were not summed directly. Instead, they were converted to six-level scores according to crop-specific target ranges and the extent of departure from those ranges before AHP weights were applied. The distinction is therefore between summarizing overall trait magnitude and assessing how closely a commercial seedling matches a crop-specific target state.

Existing composite indices and the proposed framework differ in both the information they summarize and their intended use. DQI, for example, combines total dry mass with the plant-height-to-stem-diameter ratio and the shoot-to-root dry-mass ratio to summarize seedling size and morphological balance [11]. Such indices efficiently condense a limited set of morphological attributes, but they do not directly incorporate leaf color, disease and pest status, lot uniformity, or crop-specific developmental traits [12]. Indices requiring dry mass or root measurements are also destructive, which constrains repeated assessment of large numbers of seedlings in commercial nurseries. Relationships between pre-transplant quality indices and subsequent growth may also depend on nursery conditions. In grafted tomato, Seo et al. [30] reported that DQI tended to increase with seedling age whereas relative growth rate during the first 2 weeks after transplanting tended to decrease, and that the DQI–relative-growth-rate relationship varied with nursery fertilization level. These differences indicate that the present framework and conventional composite indices summarize distinct aspects of seedling quality. Accordingly, the framework is intended to complement rather than replace established growth indices by combining crop-specific assessment traits with target ranges and expert-derived relative priorities.

The pepper seedling with the higher composite score had a greater whole-seedling dry-matter fraction and a shorter height relative to stem diameter. These observations describe the two example seedlings and do not constitute independent validation of the assessment system.

Several limitations should be considered. First, criteria were not stratified by individual cultivar, and responses across grafting status and season were pooled to derive common crop-level ranges. Seedling age appeared more likely than other traits to vary with grafting status and season, and direct comparisons of grafted and non-grafted seedlings were available from relatively few respondents. The reproducibility and applicability of the ranges should therefore be evaluated across cultivars, grafting types, seasons, plug-tray sizes, and nursery environments, with further stratification by grafting type, season, or production system as evidence accumulates [3, 31, 32]. Second, some criteria were derived from survey boundaries or measured distributions because measured datasets or numerical expert ranges were unavailable for particular traits. The effect of these differences in the data used to establish

scoring criteria should be assessed in subsequent validation. Third, stepwise scoring is simple to calculate and apply in practice, but small differences near interval boundaries can produce different scores and may not fully represent continuous biological responses. Fourth, all leaf-color examples selected by at least one expert were retained, so the current binary criterion does not account for selection frequency or degree of expert agreement. Fifth, the worked examples were intended to demonstrate calculation and interpretation; they do not validate the composite score as a biological threshold or as a predictor of post-transplant performance. The current ranges and penalty widths should therefore be treated as initial criteria that can be revised as independent validation data become available.

Conclusions

This study developed 0–100 seedling quality assessment systems for pepper, tomato, watermelon, kimchi cabbage, and cucumber by combining crop-specific trait sets, expert-derived AHP weights, and standardized scoring intervals. Disease and pest status consistently received the highest priority, with uniformity and seedling age also receiving relatively high weights, while the first flower node in pepper, the first inflorescence node in tomato, and leaf length and width in kimchi cabbage represented crop-specific developmental or morphological information. The framework offers a common calculation structure for comparing seedlings and production lots and for communicating quality criteria between nursery operators and growers. Because the current weights and ranges are based on expert judgment and limited measured datasets, the framework should be regarded as an initial system. Validation across independent seedling populations and production environments is needed to test reproducibility, relationships with post-transplant growth and productivity, convergence with established quality indices, and sensitivity to changes in weights and scoring intervals.

Abbreviations

AHP, analytic hierarchy process; CI, consistency index; CIELAB, CIE L*a*b* color space; CR, consistency ratio; DM, whole-seedling dry matter content; DQI, Dickson quality index; RGB, red-green-blue; RI, random index.

Declarations

Ethics approval and consent to participate

At the institutional project-planning and review stage, the research project was determined not to require Institutional Review Board review. Accordingly, no separate IRB review was conducted. The survey collected professional opinions from nursery professionals on seedling quality assessment criteria, and no personally identifiable information was collected or reported. The purpose of the survey was explained to the participants, who agreed to participate voluntarily.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

HJL conceived and designed the study, conducted the expert survey, performed the AHP analysis and seedling score calculations, and drafted the manuscript. JGL, YGK (Yang Gyu Ku), and YK contributed to study-planning discussions and provided crop-specific measured seedling datasets. TCS, SHW, MS, and YGK (Youg Gu Kang) supported study implementation. All authors read and approved the final manuscript.

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Availability of data and materials

The measurements used to calculate the growth-related indices for the two pepper seedlings are provided in Additional file 1. The remaining datasets supporting this study have not yet been publicly deposited because public release is planned after completion of the overarching RDA-funded project and the applicable institutional data-release procedures. In the meantime, these datasets are available from the corresponding author on reasonable request, subject to applicable RDA data-sharing procedures.

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Appendix

The appendix provides detailed standard-score intervals for each crop. Quantitative traits other than uniformity are presented on the z-score scale, whereas uniformity is presented on its original 0–1 scale. When a single score corresponds to intervals below and above the target range, the two intervals are separated by a semicolon. Z-score boundaries are reported to two decimal places to preserve the calculated scoring criteria.

Only quantitative traits are included in the interval tables. Qualitative traits, including leaf color and disease and pest status, are omitted because they are scored using predefined binary criteria.

Appendix Table 1. Standard score intervals for pepper seedling quality traits.

Trait	1.0	0.8	0.6	0.4	0.2	0
Plant height	0.39–0.85; 0.85–1.30	−0.01–0.39; 1.30–1.50	−0.41–−0.01; 1.50–1.71	−0.82–−0.41; 1.71–1.91	−1.22–−0.82; 1.91–2.12	−1.63–−1.22; 2.12–2.33
Number of nodes	−0.54–0.18; 0.18–0.89	−0.90–−0.54; 0.89–1.11	−1.26–−0.90; 1.11–1.32	−1.62–−1.26; 1.32–1.54	−1.97–−1.62; 1.54–1.75	−2.33–−1.97; 1.75–1.97
Stem diameter	0.22–1.11; 1.11–2.00	−0.27–0.22; 2.00–4.85	−0.77–−0.27; 4.85–7.69	−1.27–−0.77; 7.69–10.54	−1.77–−1.27; 10.54–13.39	−2.27–−1.77; 13.39–16.23
Number of leaves	−0.70–−0.36; −0.36–−0.03	−0.76–−0.70; −0.03–0.61	−0.83–−0.76; 0.61–1.25	−0.90–−0.83; 1.25–1.88	−0.96–−0.90; 1.88–2.52	−1.03–−0.96; 2.52–3.15
Leaf area	−0.56–−0.18; −0.18–0.19	−0.72–−0.56; 0.19–0.72	−0.88–−0.72; 0.72–1.24	−1.04–−0.88; 1.24–1.76	−1.20–−1.04; 1.76–2.28	−1.36–−1.20; 2.28–2.80
Seedling age	−0.09–1.38; 1.38–2.86	−0.45–−0.09; 2.86–3.34	−0.80–−0.45; 3.34–3.81	−1.16–−0.80; 3.81–4.28	−1.51–−1.16; 4.28–4.76	−1.87–−1.51; 4.76–5.23
First flower node	−0.46–0.11; 0.11–0.67	−0.80–−0.46; 0.67–0.79	−1.15–−0.80; 0.79–0.91	−1.50–−1.15; 0.91–1.04	−1.84–−1.50; 1.04–1.16	−2.19–−1.84; 1.16–1.28
Uniformity[z]	≥0.83	0.67–0.83	0.50–0.67	0.33–0.50	0.17–0.33	0.00–0.17

[z] Uniformity was scored directly on the original 0–1 scale without z-score standardization; all other intervals are based on z-scores. For the first flower node, seedlings without a visible first flower were assigned a score of 0; the intervals shown apply only to seedlings with an emerged flower.

Appendix Table 2. Standard score intervals for tomato seedling quality traits.

Trait	1.0	0.8	0.6	0.4	0.2	0
Plant height	0.73–1.00; 1.00–1.26	0.27–0.73; 1.26–1.48	−0.19–0.27; 1.48–1.69	−0.65–−0.19; 1.69–1.91	−1.10–−0.65; 1.91–2.12	−1.56–−1.10; 2.12–2.34
Number of nodes	−0.65–0.09; 0.09–0.84	−0.85–−0.65; 0.84–1.24	−1.05–−0.85; 1.24–1.63	−1.25–−1.05; 1.63–2.03	−1.45–−1.25; 2.03–2.43	−1.65–−1.45; 2.43–2.83
Stem diameter	0.25–2.11; 2.11–3.98	−0.00–0.25; 3.98–5.97	−0.25–−0.00; 5.97–7.96	−0.50–−0.25; 7.96–9.95	−0.75–−0.50; 9.95–11.94	−1.00–−0.75; 11.94–13.93
Number of leaves	0.11–0.83; 0.83–1.54	−0.31–0.11; 1.54–2.68	−0.74–−0.31; 2.68–3.82	−1.17–−0.74; 3.82–4.96	−1.60–−1.17; 4.96–6.10	−2.02–−1.60; 6.10–7.24
Leaf area	−0.87–−0.06; −0.06–0.75	−1.03–−0.87; 0.75–1.12	−1.18–−1.03; 1.12–1.48	−1.34–−1.18; 1.48–1.84	−1.49–−1.34; 1.84–2.20	−1.65–−1.49; 2.20–2.57
Seedling age	0.44–1.23; 1.23–2.02	−0.13–0.44; 2.02–2.61	−0.70–−0.13; 2.61–3.20	−1.27–−0.70; 3.20–3.79	−1.83–−1.27; 3.79–4.38	−2.40–−1.83; 4.38–4.97
First inflorescence node	−0.53–0.03; 0.03–0.59	−0.87–−0.53; 0.59–0.93	−1.20–−0.87; 0.93–1.26	−1.54–−1.20; 1.26–1.60	−1.87–−1.54; 1.60–1.94	−2.21–−1.87; 1.94–2.27
Uniformity[z]	≥0.83	0.67–0.83	0.50–0.67	0.33–0.50	0.17–0.33	0.00–0.17

[z] Uniformity was scored directly on the original 0–1 scale without z-score standardization; all other intervals are based on z-scores. For the first inflorescence node, seedlings without a visible first inflorescence were assigned a score of 0; the intervals shown apply only to seedlings with an emerged inflorescence.

Appendix Table 3. Standard score intervals for watermelon seedling quality traits.

Trait	1.0	0.8	0.6	0.4	0.2	0
Plant height	0.08–0.31; 0.31–0.55	−0.23–0.08; 0.55–1.12	−0.53–−0.23; 1.12–1.70	−0.83–−0.53; 1.70–2.27	−1.14–−0.83; 2.27–2.84	−1.44–−1.14; 2.84–3.42
Number of nodes	−1.20–−0.91; −0.91–−0.62	−1.43–−1.20; −0.62–0.07	−1.66–−1.43; 0.07–0.76	−1.89–−1.66; 0.76–1.45	−2.12–−1.89; 1.45–2.14	−2.35–−2.12; 2.14–2.83
Stem diameter	−0.47–2.55; 2.55–5.57	−0.96–−0.47; 5.57–6.77	−1.44–−0.96; 6.77–7.98	−1.92–−1.44; 7.98–9.19	−2.41–−1.92; 9.19–10.40	−2.89–−2.41; 10.40–11.61
Number of leaves	−1.73–−1.10; −1.10–−0.47	−1.99–−1.73; −0.47–0.42	−2.24–−1.99; 0.42–1.31	−2.49–−2.24; 1.31–2.20	−2.75–−2.49; 2.20–3.08	−3.00–−2.75; 3.08–3.97
Leaf area	−0.62–0.06; 0.06–0.75	−0.98–−0.62; 0.75–1.00	−1.34–−0.98; 1.00–1.26	−1.70–−1.34; 1.26–1.52	−2.06–−1.70; 1.52–1.77	−2.42–−2.06; 1.77–2.03
Seedling age	0.57–2.58; 2.58–4.59	0.03–0.57; 4.59–5.40	−0.51–0.03; 5.40–6.20	−1.04–−0.51; 6.20–7.01	−1.58–−1.04; 7.01–7.81	−2.12–−1.58; 7.81–8.62
Uniformity[z]	≥0.83	0.67–0.83	0.50–0.67	0.33–0.50	0.17–0.33	0.00–0.17

[z] Uniformity was scored directly on the original 0–1 scale without z-score standardization; all other intervals are based on z-scores.

Appendix Table 4. Standard score intervals for kimchi cabbage seedling quality traits.

Trait	1.0	0.8	0.6	0.4	0.2	0
Leaf length	−1.43–−0.99; −0.99–−0.54	−1.55–−1.43; −0.54–0.17	−1.67–−1.55; 0.17–0.88	−1.79–−1.67; 0.88–1.60	−1.91–−1.79; 1.60–2.31	−2.03–−1.91; 2.31–3.02
Leaf width	−0.80–−0.13; −0.13–0.53	−0.93–−0.80; 0.53–1.06	−1.06–−0.93; 1.06–1.59	−1.19–−1.06; 1.59–2.11	−1.33–−1.19; 2.11–2.64	−1.46–−1.33; 2.64–3.17
Number of leaves	−0.21–1.05; 1.05–2.30	−0.54–−0.21; 2.30–2.46	−0.87–−0.54; 2.46–2.63	−1.21–−0.87; 2.63–2.80	−1.54–−1.21; 2.80–2.96	−1.87–−1.54; 2.96–3.13
Leaf area	−0.73–−0.19; −0.19–0.36	−0.85–−0.73; 0.36–0.96	−0.97–−0.85; 0.96–1.56	−1.10–−0.97; 1.56–2.15	−1.22–−1.10; 2.15–2.75	−1.34–−1.22; 2.75–3.35
Seedling age	−0.26–0.48; 0.48–1.21	−0.46–−0.26; 1.21–1.70	−0.65–−0.46; 1.70–2.20	−0.85–−0.65; 2.20–2.69	−1.05–−0.85; 2.69–3.18	−1.24–−1.05; 3.18–3.67
Uniformity[z]	≥0.83	0.67–0.83	0.50–0.67	0.33–0.50	0.17–0.33	0.00–0.17

[z] Uniformity was scored directly on the original 0–1 scale without z-score standardization; all other intervals are based on z-scores.

Appendix Table 5. Standard score intervals for cucumber seedling quality traits.

Trait	1.0	0.8	0.6	0.4	0.2	0
Plant height	0.93–1.37; 1.37–1.81	0.53–0.93; 1.81–2.09	0.13–0.53; 2.09–2.37	−0.28–0.13; 2.37–2.65	−0.68–−0.28; 2.65–2.93	−1.08–−0.68; 2.93–3.21
Number of nodes	−0.38–0.87; 0.87–2.11	−0.88–−0.38; 2.11–2.36	−1.37–−0.88; 2.36–2.61	−1.87–−1.37; 2.61–2.86	−2.37–−1.87; 2.86–3.11	−2.87–−2.37; 3.11–3.36
Stem diameter	1.39–4.58; 4.58–7.78	0.60–1.39; 7.78–10.77	−0.19–0.60; 10.77–13.75	−0.98–−0.19; 13.75–16.74	−1.77–−0.98; 16.74–19.72	−2.56–−1.77; 19.72–22.71
Number of leaves	−0.61–−0.12; −0.12–0.37	−0.93–−0.61; 0.37–0.81	−1.24–−0.93; 0.81–1.24	−1.56–−1.24; 1.24–1.67	−1.87–−1.56; 1.67–2.11	−2.19–−1.87; 2.11–2.54
Leaf area	−0.72–0.04; 0.04–0.81	−0.94–−0.72; 0.81–1.24	−1.15–−0.94; 1.24–1.67	−1.37–−1.15; 1.67–2.09	−1.58–−1.37; 2.09–2.52	−1.80–−1.58; 2.52–2.95
Seedling age	0.52–2.14; 2.14–3.75	0.20–0.52; 3.75–4.39	−0.12–0.20; 4.39–5.04	−0.44–−0.12; 5.04–5.68	−0.77–−0.44; 5.68–6.33	−1.09–−0.77; 6.33–6.97
Uniformity[z]	≥0.83	0.67–0.83	0.50–0.67	0.33–0.50	0.17–0.33	0.00–0.17

[z] Uniformity was scored directly on the original 0–1 scale without z-score standardization; all other intervals are based on z-scores.

Figures

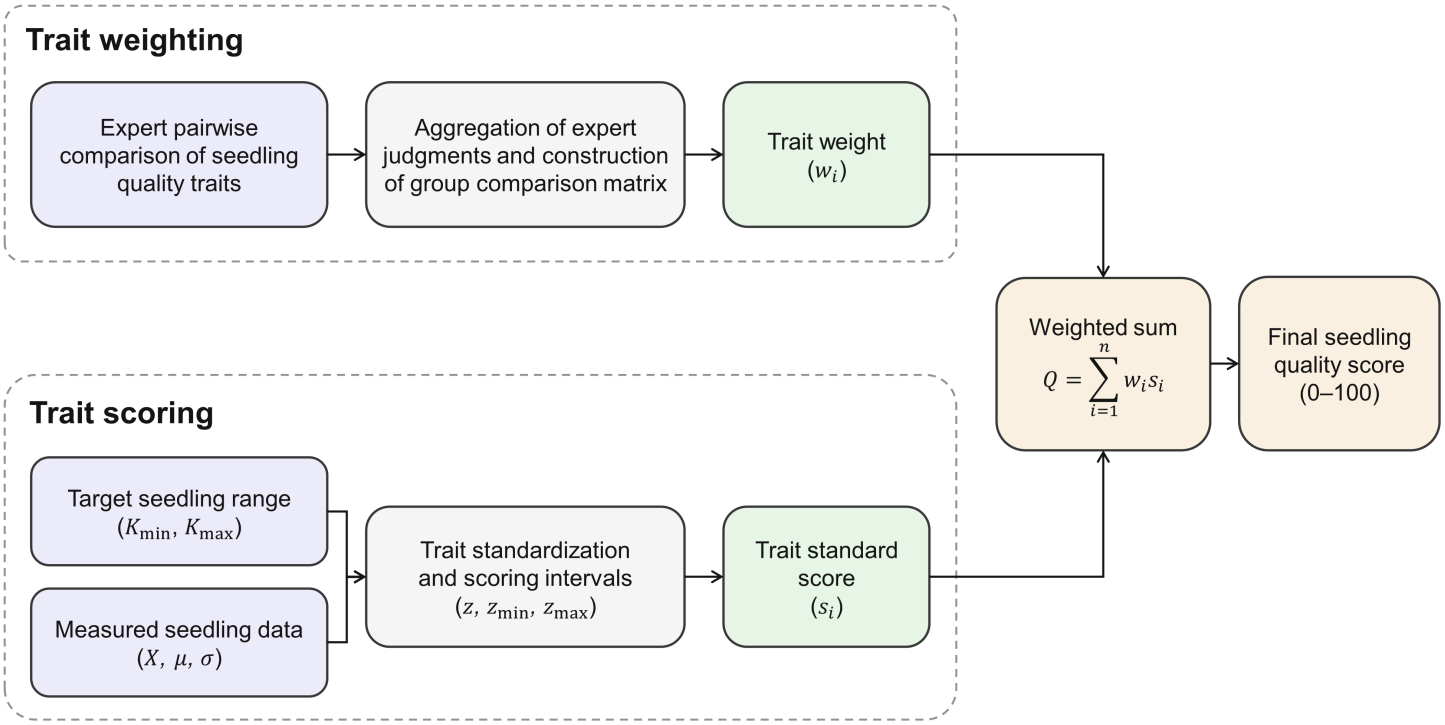


Figure 1

Framework for developing and applying the vegetable seedling quality assessment system.

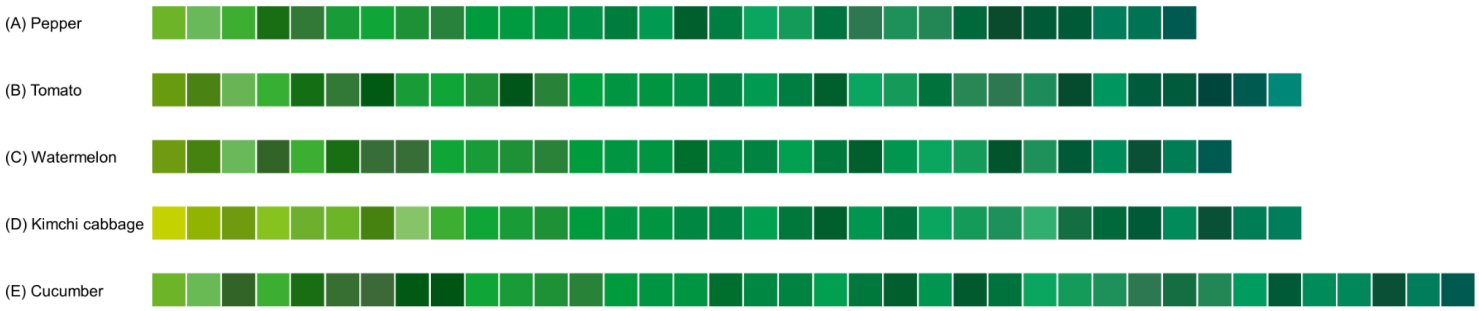


Figure 2

Leaf-color examples selected by nursery experts for five vegetable crops. Panels show (A) pepper, (B) tomato, (C) watermelon, (D) kimchi cabbage, and (E) cucumber. Respondents could select more than one leaf color for each crop, and all colors selected by at least one respondent were included. Each block represents one selected leaf-color example. Within each crop, blocks are arranged in ascending order of CIELAB hue angle, with lightness (L*) as a secondary sorting criterion, for visual clarity; this order does not indicate selection frequency or preference. Summary statistics of the CIE L*a*b* coordinates are provided in Additional file 2.

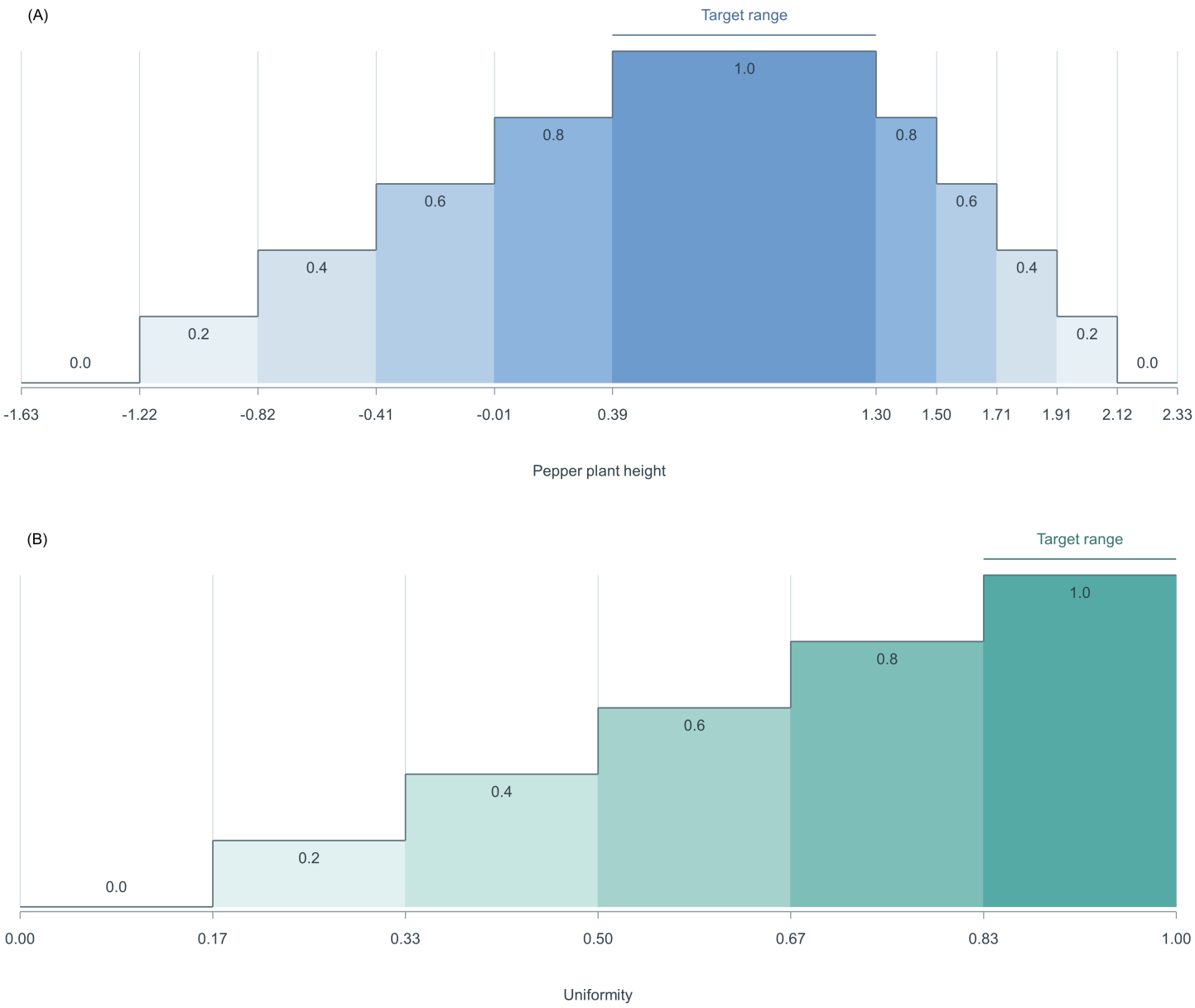


Figure 3

Examples of trait-score intervals for pepper plant height and uniformity. Plant-height intervals are shown on the z-score scale, whereas uniformity is shown on its original 0–1 scale. Numbers within the blocks indicate trait scores.

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