Received: 3 December 2025 | Accepted: 8 May 2026

DOI: 10.1002/agj2.70448

Agronomy Journal

ORIGINAL ARTICLE

Agronomy, Soils, and Environmental Quality

Defining the growth stages of mungbean (*Vigna radiata* L.) using the BBCH scale

Venkata Naresh Boddepalli | **Arti Singh**

Department of Agronomy, Iowa State University, Ames, Iowa, USA

Correspondence
Arti Singh, Department of Agronomy, Iowa State University, Ames, IA, USA. Email: arti@iastate.edu

Assigned to Associate Editor Dwarika Bhattarai.

Funding information
United States Department of Agriculture; National Institute of Food and Agriculture, Grant/Award Numbers: #2022–67013-37120, #2026-67013-45812; RF Baker Center for Plant Breeding; Department of Agronomy

Abstract

Mungbean (*Vigna radiata* L.) is a short-duration, protein-rich legume essential for diverse cropping systems and the emerging plant-based protein industry. Despite its growing global footprint, a standardized phenological framework for accurately scheduling management practices, applying agrochemicals, and developing robust crop simulation models is currently lacking. To address this gap, the objective of this study was to systematically define and characterize mungbean growth stages for the first time using the universal two-digit BBCH (Biologische Bundesanstalt, Bundessortenamt, und Chemische Industrie) scale. This study documented and illustrated the key growth stages of mungbean from germination to maturity, correlating them with days after planting and accumulated growing degree days. It outlines the principal growth stages (PS) as follows: germination (PS-0), leaf development (PS-1), stem elongation (PS-3), flower bud development (PS-5), flowering (PS-6), fruit development (PS-7), and ripening (PS-8). Most importantly, this BBCH growth stages chart provides a practical tool for researchers and growers to standardize crop management practices, develop simulation models, and assess performance under various environmental conditions. Ultimately, this standardized scale enhances the precision of timing agricultural interventions, thereby supporting improved mungbean production.

Plain Language Summary

A unified growth chart that defines each crop stage in terms of days after planting and growing degree days is essential for effective crop management. Despite an increasing global demand, no standardized Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie chart exists for mungbean to guide their growth and development from planting to maturity. This research aimed to define each growth stage using a two-digit BBCH code, which is linked to corresponding days after planting and accumulated growing degree days. The newly developed BBCH chart provides a

Abbreviations: BBCH, Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie; C.d, degree-days Celsius; DAP, days after planting; GDD, growing degree days; TTA, accumulated thermal time; TTd, daily thermal time.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2026 The Author(s). *Agronomy Journal* published by Wiley Periodicals LLC on behalf of American Society of Agronomy.

clear and uniform way to describe mungbean growth stages. This standardized framework will help researchers and growers better understand how mungbean respond to different environments and improve their integrated pest management decisions, advancing mungbean production and breeding.

1 | INTRODUCTION

The global population is estimated to reach 9.7 billion by 2050 (Ritchie et al., 2023), intensifying concerns about food security and the need for sustainable increases in agricultural productivity (Oluwole et al., 2023). To address these challenges, diversified cropping systems have emerged as a promising strategy, offering both environmental and nutritional benefits (Douyon et al., 2022; Yang et al., 2024). Among these systems, the integration of legumes into crop rotations has gained significant attention due to their ability to increase yields of subsequent crops by 38%, reduce greenhouse gas emissions, and improve soil health through biological nitrogen fixation (Kebede, 2021; Mesfin et al., 2023; Yang et al., 2024). In addition, legume crops are rich in proteins, carbohydrates, essential amino acids, micronutrients, and vitamins. They can play a crucial role in combating malnutrition, particularly in developing countries where access to animal-based proteins is limited (Langyan et al., 2022; Samal et al., 2023). The interest in plant-based protein sources also aligns with sustainable dietary practices and contributes to reducing the environmental footprint of food production (Langyan et al., 2022; Viroli et al., 2023). As demand for sustainable and nutritious food sources grows, a practical strategy is to integrate diverse legumes into global agricultural systems to enhance food security, improve nutrition, and promote environmental sustainability (Lisciani et al., 2024).

Mungbean (*Vigna radiata* L.), a food grain legume that originated in the Indo-Burma region, is widely cultivated in Asian countries with increasing popularity in other regions, including Africa, Australia, and parts of the United States (Nair & Schreinemachers, 2020; Somta et al., 2022; Wilbur et al., 2025). Its increasing adoption is driven by its high nutritional value, particularly its digestible proteins (24%–28% on a dry weight basis), minerals, vitamins, and essential micronutrients, and its economic importance (Liang et al., 2020; USDA Natural Resources Conservation Service, 2024). Mungbean adaptability to warm climates and its short duration (65–75 days after planting [DAP]), coupled with low input requirement, make it a versatile crop that can be integrated into various agricultural systems, such as monoculture, double cropping, or as a cover crop (Batzer, Singh, Rairdin, et al., 2022; Jaya et al., 2021; Koyejo et al., 2021). In the US Midwest, these unique traits allow it to seamlessly utilize existing soybean (*Glycine max* L.) infrastructure with minimal adjustments. Consequently, mungbean serves as a valuable complementary crop for regional farmers seeking to diversify rotations or capitalize on delayed planting windows (Batzer, Singh, Platner, et al., 2022).

Understanding the phenological growth stages of mungbean is essential for effective production management. Such knowledge enables synchronization of management practices with critical growth stages, crop monitoring, and optimization of crop performance and resilience (Fotouo Makouate & Zude-Sasse, 2025; Grimes et al., 2025; Y. Liu et al., 2023; Schieler et al., 2023; You et al., 2022). A standardized framework for describing plant growth stages is indispensable for accurate crop management, modeling, and evaluation under various environmental conditions and input responses (Dambreville et al., 2015; Wang et al., 2024). The BBCH (Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie) scale is widely accepted for this purpose and is a universal decimal coding system that uses a two-digit code to systematically describe crop ontogeny. In this framework, the first digit (0–9) represents the principal macro-stage of development (e.g., germination, flowering, and ripening), while the second digit (0–9) denotes the specific secondary micro-stage or percentage of completion within that principal phase. This standardized numerical format provides an unambiguous, universal system for describing and comparing growth stages across different crop species and research disciplines (Awachare & Upreti, 2020; Taghavi et al., 2022).

Although mungbean is globally cultivated on over 7 million ha (Nair & Schreinemachers, 2020; Somta et al., 2022), a standardized growth-stage chart according to the BBCH scale remains unavailable. This can be a caveat for researchers, agronomists, and farmers to optimize management practices, develop accurate crop models, and assess performance under diverse conditions. To address this gap, we proposed this study with a twofold aim: (1) to define phenological growth stages according to the two-digit BBCH scale and (2) to record the number of DAP and calculate the growing degree days (GDD) required for each growth stage in the US Midwest.

2 | MATERIALS AND METHODS

2.1 | Experimental location

This study was carried out over two growing seasons (2023 and 2024) at the Iowa State University Research Farm on

TABLE 1 Key features of the two mungbean cultivars (ISU mung G1, ISU mung G2) utilized in this study.

Trait	ISU mung G1	ISU mung G2
Origin	ISU, Iowa	ISU, Iowa
Pedigree	AVMU0201 × PI 425513	AVMU0201 × PI 377167
Growth habit	Erect	Erect
Days to first flower	39	41
Days to 80% mature pods	68	67
1000-Seed weight (g)	39.3	34.1
Seed % protein (dry basis)	24.19	24.25
Plant height (at maturity) (cm)	49.8	49.8
Seed texture	Dull	Shiny
Seed color	Green	Green

Core Ideas

- Mungbean is a versatile, protein-rich grain legume suitable for diversified and sustainable cropping systems.
- The phenological development of mungbean from germination to maturity was systematically defined using the two-digit Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) scale for the first time.
- The proposed BBCH chart can serve as a unified framework for researchers and growers to synchronize phenological observations, improve crop management scheduling, and support model simulations across environments.

Agricultural Engineering and Agronomy (AEA) near Boone, IA. In 2023, the trial was planted on 1 June at the AEA farm (42°01′14.9″ N, 93°46′05.1″ W). In 2024, planting took place on June 2 at two locations: the AEA farm (42°01′08.0″ N, 93°46′18.4″ W) and the Bruner farm (42°00′51.5″ N, 93°43′52.2″ W). All sites were characterized by silty clay-loam soils typical of the Des Moines Lobe landform. The previous crop at all locations was corn (*Zea mays* L.).

2.2 | Plant material and experimental design

Two mungbean cultivars, ISU Mung G1 and ISU Mung G2 (Table 1), were utilized for this study. These two lines were developed by the Iowa State University (ISU) breeding program using a modified bulk method with bi-parental crosses for Midwestern growing conditions. The seed of each cultivar was planted in a plot with 3 m rows, spaced 75 cm apart with 20 cm intervals at a depth of 2.5 cm, using a Randomized Complete Block Design with five replications at each location. Standard agronomic practices were maintained throughout the 2023 and 2024 growing seasons. Soil fertility was managed prior to planting and in-season based on field-specific requirements. Basal dry fertilizer applications included potash (0-0-60) at 200–223 kg/ha, MicroEssentials SZ (MESZ; 12-40-0-10S-1 Zn) at 202 kg/ha, and Super-Cal SO4 (pelletized calcium sulfate) at 119 kg/ha. Nitrogen requirements were met using field-specific applications of anhydrous ammonia (82% N) at 275 kg/ha, dry urea (46% N) at 145–359 kg/ha, or liquid 32% UAN at 66–162 L/ha. The experiments were conducted under strictly rainfed conditions. A pre-emergence herbicide, S-metolachlor (Dual Magnum; 83.7% a.i.) at 1.5–2.3 L/ha, was applied 15 days prior to planting, followed by manual weeding as needed throughout the season.

2.3 | Weather data

Daily weather data, including maximum temperature (T_{max}), minimum temperature (T_{min}), relative humidity, and precipitation measurements, were obtained from the Iowa Environmental Mesonet website (Herzmann, n.d.), which were collected from on-site installed weather stations (Table S1). Figure 1 illustrates the average weekly weather parameters, mainly minimum and maximum air temperatures and precipitation observed during the study for each month and year.

2.4 | Growth stage data

The development of mungbean phenological stages was assessed using the two-digit BBCH coding system, following international standards for beans (Hack et al., 1992; Meier, 2018). The BBCH principal stages assigned were principal stage 0 (germination: VG-VE, BBCH 00-08), principal stage 1 (leaf development: VC-V2, BBCH 09-12), principal stage 3 (stem elongation: V3-V5, BBCH 30-33), principal stage 5 (flower bud development: V6, BBCH 51), principal stage 6 (flowering: R1, BBCH 60), principal stage 7 (fruit development: R2-R4, BBCH 71-79), principal stage 8 (ripening: R5-R7, BBCH 81-89), and principal stage 9 (senescence: BBCH 97-99). Observations of the phenological stages (Table S2) were recorded during the early morning hours. During rapid developmental phases (germination through flowering stages, VE to R1), observations were made every 2 days to capture the rapid transitions between stages. During slower developmental phases (pod initiation through maturity, R2 to R7), weekly observations were sufficient as stage transitions occurred more gradually. Images of the growth stages were captured using a Nikon D3500 DSLR camera. All 20

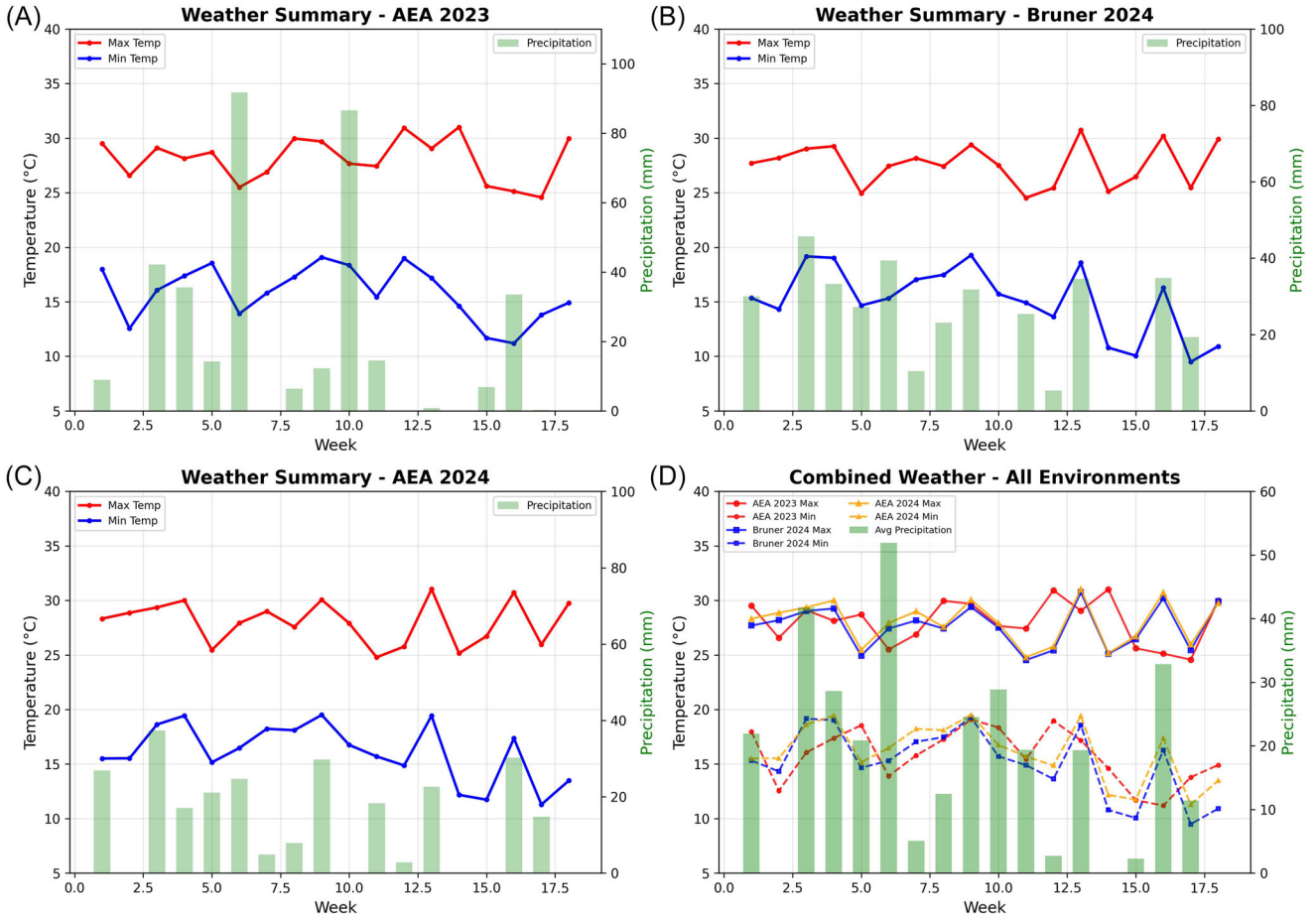


FIGURE 1 Weekly weather patterns across experimental environments during 2023–2024 growing seasons. Individual panel location-year-specific weather conditions for (A) Agricultural Engineering and Agronomy (AEA) Research Farm 2023, (B) Bruner Farm 2024, (C) Agricultural Engineering and Agronomy (AEA) Research Farm 2024, and (D) depict the comparative weather patterns across three environments.

tagged plants per plot were observed at each observation date. Plants were selected randomly at the beginning of the experiment and tagged with permanent markers for consistent identification throughout the growing season. A plot was considered to have reached a specific developmental stage when at least 50% (≥10) of the tagged plants exhibited the defining characteristics of that stage.

2.5 | GDD calculation

Thermal requirements were expressed as GDD in degree-days Celsius (˚C.d). First, the daily thermal time (*TTd*) was calculated by subtracting the base temperature ($T_b = 10^{\circ}C$) from the average of the daily maximum (T_{max}) and minimum (T_{min}) air temperatures, as shown in Equation (1) (McMaster & Wilhelm, 1997).

$$TTd = \left[\frac{T^d_{\max} + T^d_{\min}}{2}\right] - T_b \quad (1)$$

The accumulated thermal time (TTA) required to reach each phenological stage from the date of planting was then calculated by summing the *TTd* over the number of days (n) required to complete that specific stage, as shown in Equation (2) (Cavalcante et al., 2020).

$$TTA = \sum_{i=1}^{n} TTd \quad (2)$$

2.6 | Data analysis

Descriptive statistics for DAP and GDD were calculated to determine the mean and standard error for each BBCH stage across environments and cultivars (Pinzón-Sandoval et al., 2024). Phenological data (DAP and GDD) were analyzed using two complementary approaches. First, cultivar effects were tested using a linear mixed model with cultivar as a fixed effect and site-year and replicate as random effects. Second, to characterize environmental variation across the

specific site-years tested, a one-way ANOVA was conducted with site-year (AEA 2023, AEA 2024, Bruner 2024) as a fixed factor. Pairwise differences between site-years were calculated using Tukey's honestly significant difference (HSD) test with $\alpha = 0.05$. This fixed-effects approach was chosen to describe phenological responses in these specific environments rather than to generalize to a broader population of sites and years. Model residuals were assessed for normality using the Shapiro–Wilk test and *Q–Q* plots. Statistical analyses were performed in Python 3.x using pandas, numpy, scipy, and statsmodels packages.

2.7 | Growth stages sketch

The digital illustrations were generated using Adobe Photoshop for sketching and coloring and Adobe Illustrator for final layout and output, with drawing executed using a Wacom graphics tablet. After multiple iterative review sessions throughout the sketching process, the authors evaluated the final sketches for botanical accuracy by directly comparing them against high-resolution field photographs and live plant specimens. Once morphological consistency with international standards was confirmed, they were assembled into a comprehensive visual reference guide for mungbean growth stages with V/R code and corresponding DAP.

3 | RESULTS

The phenological stages of the mungbean (Table 1) were observed in relation to the chronological time (DAP), and the thermal time (cumulative degree days) for each stage was depicted in Figures 1–3, and the V/R stage alignment description was presented in Table 2 with DAP and GDD and in Table S3.

3.1 | Principal growth stage 0: Germination stage

The germination stage, including dry seed (BBCH 00) that starts imbibing water (BBCH 01). After the complete imbibition stage (BBCH 03), the radicle emergence starts from the seed (BBCH 05), followed by the emergence of the hypocotyl with cotyledons split from the seed coat (BBCH 07), and finally, the hypocotyl reaches the soil surface with a visible arch (BBCH 08), as described in the BBCH scale, as shown in Figure 3.

BBCH 09: VE stage: The emergence stage (VE) occurs when the unifoliate leaves unfurl from the cotyledons above the soil surface, reaching an accumulated thermal unit of 86˚C.d, at 6 DAP.

3.2 | Principal growth stage 1: Leaf development

BBCH 10: VC stage: This was the beginning of the leaf developmental stage, where the unifoliate leaves fully expand. The edges of the leaves did not touch and were positioned opposite each other on the stem. The development of these leaves required around 188˚C.d and was completed in 10 DAP.

BBCH 11: V1 stage: The first trifoliate leaves attached to the first node immediately above the unifoliate leaves are fully expanded and flat. Meanwhile, the second trifoliate leaf at the upper node begins to roll. This stage is marked by an accumulated thermal unit of 284˚C.d, reached approximately 17 DAP. The progression continues until the next significant growth stage.

BBCH 12: V2 stage: The second trifoliate leaf at the second node becomes fully expanded and flat, while the third trifoliate leaf at the upper node starts unrolling. This stage requires an accumulated thermal unit of 284˚C.d, which occurs about 22 DAP.

3.3 | Principal growth stage 3: Stem elongation

Stem elongation starts at the third leaf stage of the plant, while trifoliate leaves continue their expansion on different nodes. This indicates the transition from leaf development to stem elongation.

BBCH 30: V3 stage: During this stage, the third trifoliate leaf attached to the third node is fully expanded and flat, while the fourth trifoliate leaf at the upper node begins to unroll. The thermal accumulation for this stage is 341˚C.d, reaching approximately 26 DAP.

BBCH 31: V4 stage: The fourth trifoliate leaf attached to the fourth node is fully expanded and flat, while the fourth trifoliate leaf at the upper node begins to unroll. This stage is marked by an accumulated thermal unit of 393˚C.d, occurring around 30 DAP.

BBCH 32: V5 stage: During the V5 stage, the fifth trifoliate leaf attached to the fifth node is fully expanded and flat, while the sixth trifoliate leaf at the upper node starts to unroll. This stage is characterized by an accumulated thermal unit of 439˚C.d, approximately 34 DAP.

3.4 | Principal growth stage 5: Flower bud development

BBCH 51: V6 stage: At stage V6, the sixth trifoliate leaf attached to the sixth node is fully expanded and flat, and the seventh trifoliate leaf at the upper node begins unrolling. The

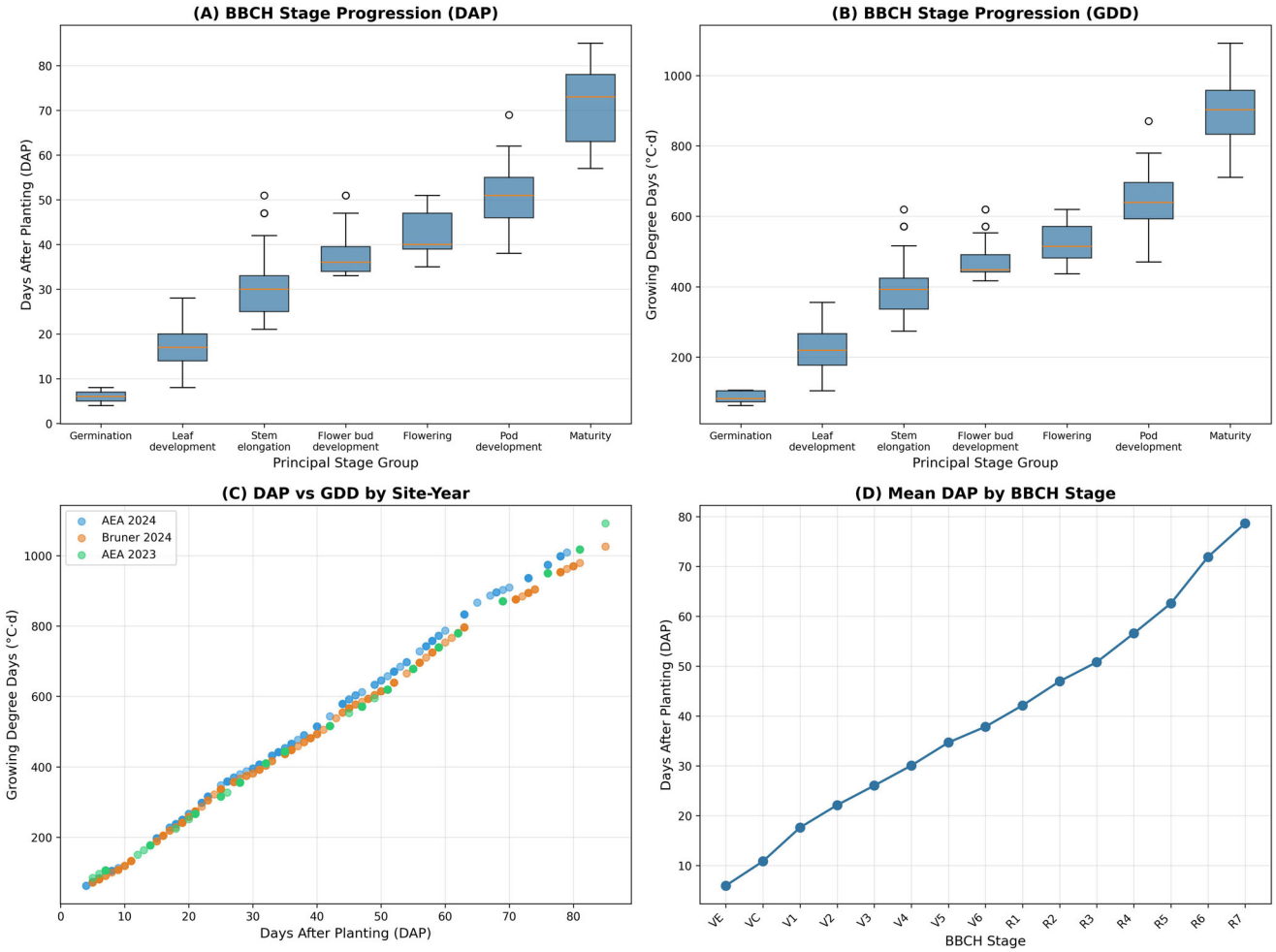


FIGURE 2 Mungbean principal growth stages progression across multiple site-years. (A). Days after planting (DAP) distribution box plots with specific Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) stages listed. (B). Accumulation of GDD with the specified base temperature (C) Relationship between DAP and GDD showing environmental interactions.

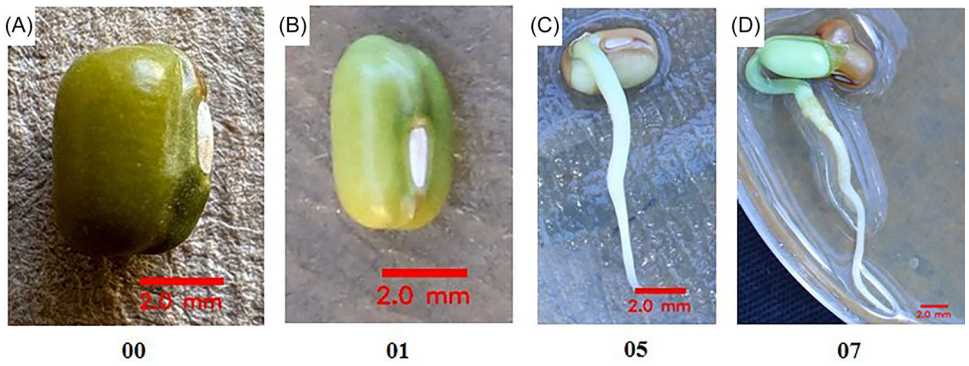


FIGURE 3 Mungbean germination stage progression according to the Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) scale: (A) dry seed (B) starting of the imbibition (C) radicle emergence from the seed (D) emergence of hypocotyl with split cotyledon, which is ready to crack the soil surface.

TABLE 2 Principal growth stage (PS) and their corresponding vegetative/reproductive (V/R) stages with descriptions for mungbean phenological stages and their mean stage (days after planting [DAP]) and thermal (GDD) timings along with their standard deviations (SD).

Principal growth stage (PS)	PS_group	BBCH code	V/R stage	V/R description	DAP_ mean	DAP_ SD	GDD_ mean	GDD_ SD	Number of plants per plot	Number of plots	Number of site-years
0	Germination	09	VE	Emergence	5.97	1.03	86.19	14.62	20	30	3
1	Leaf development	10	VC	Cotyledon development	10.84	2.5	135.67	31.76	20	30	3
		11	V1	First true leaf	17.62	2.56	226.21	30.73	20	30	3
		12	V2	Second true leaf	22.12	4.04	284.17	48.56	20	30	3
3	Stem elongation	30	V3	Third true leaf	26.03	5.03	341.22	58.23	20	30	3
		31	V4	Fourth leaf	30.06	5.81	393.53	60.11	20	30	3
		32	V5	Fifth leaf	34.68	6.25	439.3	67.37	20	30	3
5	Flower bud development	51	V6	Flower bud development	37.85	5.57	475.38	59.45	20	30	3
6	Flowering	60	R1	First flowers open	42.13	4.93	523.67	51.89	20	30	3
7	Pod development	71	R2	Pod initiation	46.97	4.68	590.53	48.79	20	30	3
		75	R3	Pod filling	50.81	4.24	639.85	50.62	20	30	3
		79	R4	Full seed	56.58	3.84	716.29	50.13	20	30	3
8	Ripening	81	R5	Beginning maturity	62.6	4.71	799.98	54.2	20	30	3
		88	R6	90% Maturity	71.92	3.56	907.86	36.1	20	30	3
		89	R7	Final maturity	78.64	2.69	983.02	33.46	20	30	3

Note: Results represent pooled data from two mungbean cultivars (ISU Mung G-1 and ISU Mung G-2) across three site-years. Cultivar effects were tested and found non-significant ($p > 0.05$ for all stages).
Abbreviation: BBCH, Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie.

inflorescence, which develops along the internodes, will begin to bear flower buds. This stage is marked by an accumulated thermal unit of 475˚C.d, occurring approximately 38 DAP. At this stage, the plants started producing flower buds.

3.5 | Principal growth stage 6: Flowering

The flowers with pale yellow petals start opening, indicating the plant's transition to the reproductive stage from the vegetative stage (Figures 4 and 5).

BBCH 60: R1 stage: The first open flower is observed at any of the three upper nodes on the main stem on 50% of the plants in the plot, marking the beginning of flowering, and this stage continues until full bloom. It requires an accumulated thermal unit of 523˚C.d, approximately 42 DAP.

3.6 | Principal growth stage 7: Pod development

During this stage, the pod initiation begins to continue elongation, and the pod filling continues until the full seed stage (Figures 4 and 5).

BBCH 71: R2 stage: Pod initiation begins with the formation of a pod approximately 1.0–2.0 cm in length and elongates up to 3.0–4.0 cm at the end of this stage on the inflorescence between the top three nodes on the main stem. An accumulated thermal unit of 590˚C.d was observed for this stage around 47 DAP.

BBCH 75: R3 stage: Pod filling begins when a pod approximately 4.0–5.0 cm long is observed at any of the top three nodes on the main stem and continues its elongation till the end of this stage. This stage requires an accumulated thermal unit of 637˚C.d, approximately 52 DAP.

BBCH 79: R4 stage: At the full seed stage, at least one to two pods in a cluster on any of the top three nodes developed constrictions between the seeds. The pods turn pale yellowish or lighter green, indicating they are ready for maturity. This stage occurs with an accumulated thermal unit of 716˚C.d, observed around 57 DAP.



FIGURE 4 Mungbean key phenological growth stages according to the two-digit Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) scale: germination (A and B); leaf development (C–E); stem elongation (G and H); flower bud development (I); flowering (J); pod development (K–M); pod maturity (N and O). A pixel to millimeter (mm) scale bar (50 mm) in red color was assigned on the bottom right corner of each image.

3.7 | Principal growth stage 8: Ripening (maturity)

The color of the pods on clusters in any of the top nodes changes from pale yellowish green to brown or black, indicating the beginning of the maturity stage. The percentage of pods that turn black or brown determines each sub-stage.

BBCH 81: R5 stage: The first pod in a cluster turns black or brown in color, indicating the beginning of maturity. The total accumulated thermal units for this stage are 800˚C.d. Subsequently, around 50% of the pods on the plant mature 66 DAP, and 75% at around 69 DAP.

BBCH 88: R6 stage: At this stage, 85%–90% of pods on the plant turn black or brown, indicating near-complete maturity to begin harvesting. This stage is reached with an accumulated thermal unit of 908˚C.d, observed at 72 DAP.

BBCH 89: R7 stage: The plant fully matures when 100% of the pods mature. This stage is reached with an

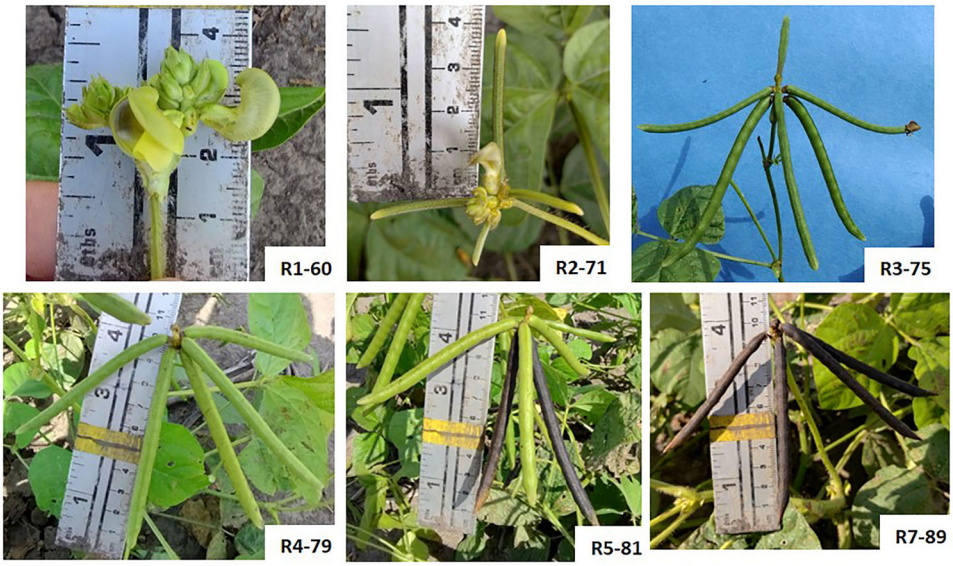


FIGURE 5 Key mungbean reproductive stages transformation from flowering (R1) to the final maturity (R7) in the ISU Mung G1 cultivar at the Bruner24 environment. Each image is annotated with the V/R growth stage and the Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) code.

accumulated thermal unit of 983°C.d, observed approximately at 79 DAP.

3.8 | Principal growth stage 8: Senescence

We were unable to observe senescence during these experiments because the two mungbean cultivars we used in this study require chemical desiccation for harvesting. The plants remain green longer after maturity (Figure 6).

4 | DISCUSSION

The two-digit BBCH scale of mungbean phenological stages provides a standardized framework that offers valuable insights into mungbean growth and development, supporting standardized management practices for yield optimization. This study aimed to delineate the growth stages of mungbean using the BBCH scale and corresponding V/R stages, which is widely recognized for its applicability across various crops (Acosta-Quezada et al., 2016; Cavalcante et al., 2020; Herraiz et al., 2015; Kishore & Mahanti, 2016; K. Liu et al., 2015; Martínez et al., 2019; Pati et al., 2020; Pinzón-Sandoval et al., 2024; Ramírez & Kallarackal, 2018; Sosa-Zuniga et al., 2017). While previous work by Pookpakdi et al. (1992) described descriptive growth stages for mungbean in Thailand, our study represents the first formal adaptation of the internationally recognized BBCH coding system for this species, enabling standardized comparisons across diverse environments and facilitating integration with crop modeling frameworks.

4.1 | Environmental effects on phenological development

This study identified that site-year environment significantly influenced all 15 phenological stages ($p < 0.05$) (Table S3), while there were no significant differences detected between the two cultivars tested ($p > 0.05$ for all stages) (Table S4). This suggests that environmental factors, particularly temperature and moisture availability, apply stronger control over mungbean phenological progression than the genetic differences between these closely related ISU cultivars. The AEA 2023 environment exhibited consistently delayed phenology compared to both 2024 environments. Tukey's HSD analysis revealed that AEA 2023 differed significantly from AEA 2024 and Bruner 2024 for most vegetative and early reproductive stages, with mean delays ranging from 5.3 days at the V1 stage to 12.2 days at the V6 (flower bud development) stage. In contrast, AEA 2024 and Bruner 2024 showed no significant differences across any growth stage, indicating similar environmental conditions at these two 2024 locations. These findings align with previous reports that environmental conditions strongly influence mungbean development rates (Dhillon, 2020; HanumanthaRao et al., 2016; Malaviarachchi et al., 2016; Rocha et al., 2025).

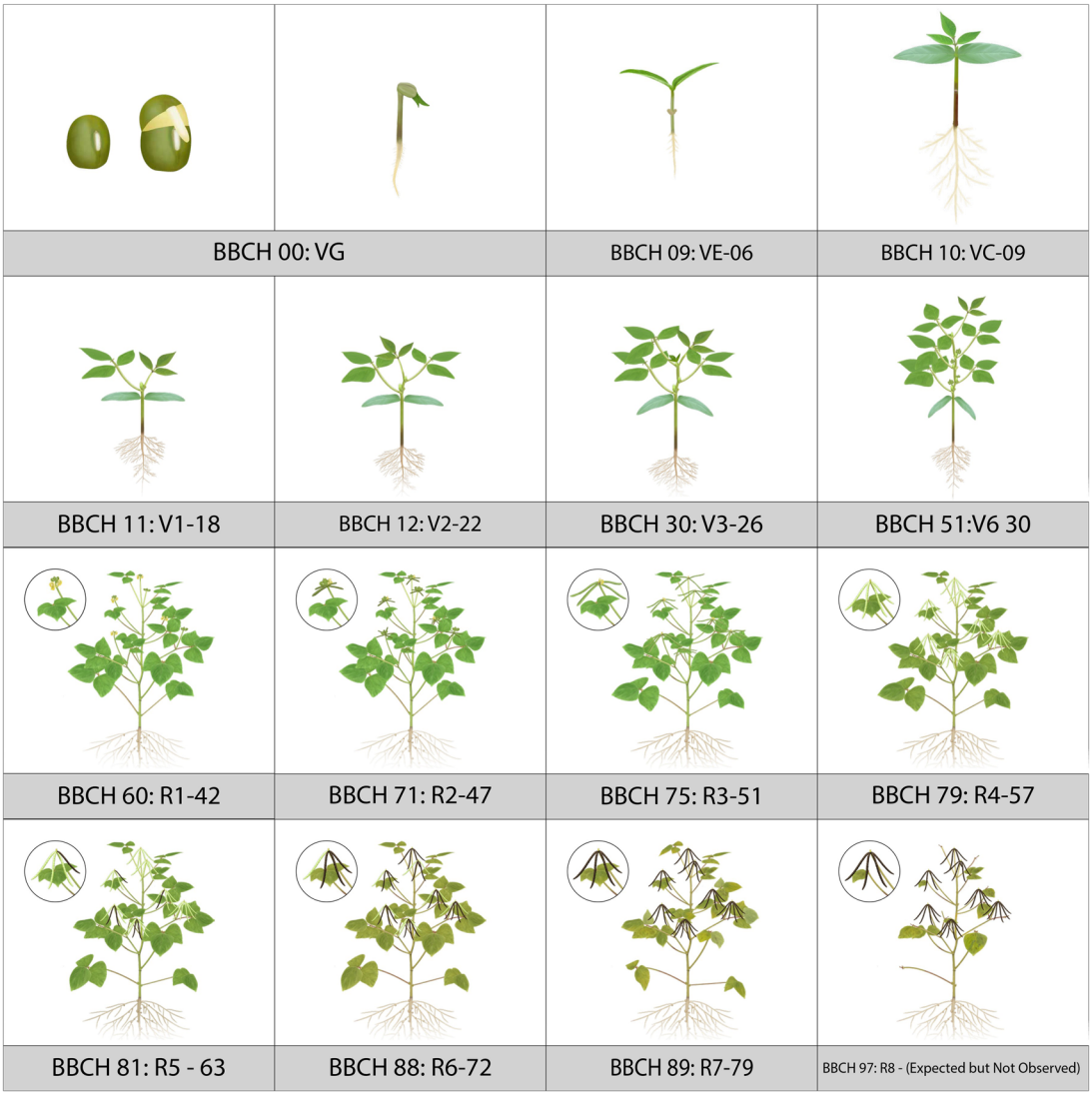


FIGURE 6 Bio-rendered sketch illustrating Mungbean growth stages according to the two-digit Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) scale and the V/R stage chart, from germination to senescence, according to their days after planting.

4.2 | Temperature effects on stage-specific development

Air temperature is a primary meteorological factor influencing crop development (Mendes et al., 2017) and plays a key role in determining crop thermal requirements. Mungbean optimal growing temperatures are between 25˚C and 35˚C, with the ideal range for growth and yield observed at 28˚C–35˚C (Bhardwaj et al., 2023; Kaur et al., 2015). During our experiments, mean maximum temperatures across all site-years ranged from 27.5˚C (Bruner 2024) to 28.0˚C (AEA 2023 and AEA 2024), placing the experimental conditions at the lower end of the optimal temperature range, and approximately 75%–80% of growing days fell within the optimal temperature range across all environments. The similar mean temperatures across environments suggest that temperature alone does not explain the observed phenological delays in AEA 2023. However, daily temperature fluctuations and the timing of temperature extremes relative to critical developmental windows may have contributed to stage-specific delays. During the germination and early leaf development stages (BBCH 09-12), which require accumulated thermal units of 86–284˚C.d, even minor temperature variations can substantially affect the rate of heat unit accumulation and, consequently, the duration of these stages.

4.3 | Precipitation, water availability, and stage-specific responses

During the experimental periods, varying total rainfall was recorded among site-years: AEA 2023 received 354 mm, Bruner 2024 received 360 mm, and AEA 2024 received 258 mm, with no supplemental irrigation provided. These

values are below the optimal rainfall distribution of 400-500 mm reported for mungbean (Bhardwaj et al., 2023), indicating that all three environments experienced some level of water deficit, and these conditions may have differentially affected specific growth stages. For instance, vegetative stages, particularly stem elongation (BBCH 30-33), showed high variability (CV = 16%–18%). The V3 through V5 stages exhibited mean delays of 9.5–11.1 days in AEA 2023 compared to the 2024 environments. Water deficit during vegetative development can reduce leaf expansion rates and delay node appearance, as the plant prioritizes root development over shoot growth under moisture-limited conditions (Islam et al., 2021). However, the higher rainfall in AEA 2023 (354 mm) unexpectedly coincided with delayed development, suggesting that rainfall distribution pattern and timing relative to growth stages may be more important than total seasonal precipitation.

Conversely, reproductive stages (BBCH 60-89) showed lower variability (CV = 3%–8%), with the coefficient of variation decreasing from 10.8% at flowering (R1) to 3.4% at final maturity (R7). This pattern indicates that plants become less sensitive once they transition to the reproductive phase, and development becomes more channeled and less sensitive to environmental fluctuations. The reduced variability in later reproductive stages may also reflect a compensation mechanism whereby plants under earlier water stress accelerate their transition to reproductive development, as reported for other grain legumes under abiotic stress (Bangar et al., 2019; HanumanthaRao et al., 2016).

4.4 | Stage-specific variability and practical implications

The variability analysis revealed distinct patterns between growth phases. Early developmental stages (VE through V2) exhibited high standard deviations (CV = 17%–23%), with the cotyledon stage (VC) showing the highest variability (CV = 23.0%), implicating that management decisions based solely on calendar DAP may be unreliable for scheduling early-season interventions such as herbicide applications or the first scouting for seedling pests. Similarly, the stem elongation phase (V3–V5) maintained moderate-to-high variability (CV = 16%–18%), reflecting the sensitivity of vegetative growth to environmental conditions, and water stress may be one of the factors affecting plant architecture and, ultimately, yield potential. The consistent 9-11-day delays observed in AEA 2023 during stem elongation suggest that it responds to environmental variation. In contrast, the ripening stages (R5-R7) showed significantly lower variability (CV = 3%–8%), indicating more predictable maturation timing, which might be advantageous for harvest scheduling decisions, particularly in mechanized production systems where coordinating desiccation timing with harvest operations is critical to minimize pod shattering and seed quality losses.

4.5 | GDD as a phenology predictor

The GDD provides a more consistent framework for predicting phenological stages than calendar days alone, as it integrates daily temperature effects into a cumulative measure (Fotouo Makouate & Zude-Sasse, 2025; Grimes et al., 2025; Nxumalo et al., 2026; Schieler et al., 2023). In this study, we employed a base temperature (T_b) of 10°C following the method of McMaster and Wilhelm (1997). While this base temperature is commonly used for warm-season legumes, it is important to acknowledge that optimal base temperatures for mungbean may vary, ranging from 8°C to 12°C, depending on the developmental stage (Malaviarachchi et al., 2016). Future research should validate the appropriate base temperature for mungbean across diverse environments to improve GDD-based predictions.

The linear relationship between DAP and GDD (Figure 2C) showed environmental effects: AEA 2023 accumulated thermal units at a slower rate per calendar day than in 2024. This pattern suggests that, despite similar mean temperatures, the AEA 2023 environment may have experienced conditions that reduced the effective thermal accumulation rate, potentially due to cooler night temperatures or temperature fluctuations that reduced the *TTd* contribution.

4.6 | Data limitations and reliability considerations

Some observations were missing in the AEA 2023 environment, primarily due to rabbit herbivory that damaged plant stands in several plots and lodging during the early vegetative stages. Additionally, the V6 (flower bud development) stage was not consistently observed across all environments, as the transition from V6 to R1 (flowering) can occur rapidly under favorable conditions, making this stage difficult to capture during routine observation intervals. The flower bud development stage (BBCH 51) may progress quickly to flowering within 2–4 days, particularly when temperatures are within the optimal range, resulting in some missed observations when scouting was conducted on alternate days or at weekly intervals. These data limitations should be considered when applying the stage-specific DAP and GDD values presented in Table 2. The values represent pooled estimates across available observations from all environments, and local calibration may be necessary for specific regions or growing conditions.

4.7 | Relationship to previous mungbean staging systems

The V/R staging system commonly used for mungbean (Pookpakdi et al., 1992) provides descriptive growth-stage terminology but lacks standardized numerical coding that enables cross-species comparisons. Our BBCH adaptation maintains the familiar V/R nomenclature while linking each stage to the internationally recognized two-digit BBCH framework. This dual-coding approach (Table S5) facilitates communication among researchers and growers familiar with either system while enabling integration with crop models and decision-support tools that use BBCH codes. The flowering stage (BBCH 60; R1) occurred at approximately 42 DAP (523˚C.d), consistent with the 39–41 days to first flower reported for these cultivars in variety trials (Table 1). The period from flowering (R1) to final maturity (R7) spanned approximately 37 days, placing the total crop cycle at 79 DAP (983˚C.d). This duration falls within the 65–75 day range typical for short-duration mungbean cultivars adapted to temperate environments (Batzer, Singh, Rairdin, et al., 2022; Sandhu & Singh, 2021; Wilbur et al., 2025).

4.8 | Applications for crop management and modeling

Integrating the BBCH chart with GDD models enables adjusting planting times, scheduling irrigation precisely, and making informed pest management decisions. The stage-specific GDD requirements reported in Table 2 provide baseline thermal time thresholds that can be incorporated into crop simulation models. For integrated pest management, knowing the precise growth stage enables better timing of scouting efforts and pesticide applications, as different pest complexes affect specific growth stages (Heidt, 2024). The pod development stage (BBCH 71-79) is particularly vulnerable to insect pests, including pod borers and seed-feeding insects (Heidt, 2024). Our data indicate this stage spans approximately 10 days (47–57 DAP), providing a defined window for targeted pest management interventions.

4.9 | Limitations and future directions

A few limitations should be considered when applying these results. First, the study was conducted at two locations in central Iowa over 2 years; validation across broader geographic regions and additional growing seasons would strengthen the generalizability of the GDD requirements. Second, both cultivars were developed by the same breeding program and share similar genetic backgrounds; testing with genetically diverse mungbean accessions may reveal cultivar-specific phenological responses. Third, all experiments were conducted under rainfed conditions; the phenological responses under irrigated production systems may differ, and future studies should characterize stage-specific water requirements using crop coefficients (Kc) and evapotranspiration estimates. Future research should examine the effects of controlled water stress at specific growth stages to better characterize stage-specific drought sensitivity. Additionally, investigating the relationship between phenological stages and pest/disease occurrence could support the development of stage-based integrated pest management guidelines for mungbean production in the Midwest region.

5 | CONCLUSION

This study establishes the first standardized two-digit BBCH scale and GDD model for mungbean phenology. By demonstrating that environmental factors exert a stronger influence on developmental timing than genetic variation among adapted cultivars, this research provides a robust, unified framework for predicting mungbean growth. For researchers and growers, particularly in the US Midwest, integrating this BBCH chart with GDD enables precise scheduling of critical management practices, such as irrigation and pest control, during sensitive reproductive windows. As global demand for plant-based proteins continues to rise, integrating versatile legumes such as mungbean into diverse cropping systems will become increasingly essential. This standardized phenological guide serves as a foundational resource to optimize mungbean agronomy, support crop modeling, and ultimately enhance production to meet the needs of the plant-based protein industry.

AUTHOR CONTRIBUTIONS

Venkata Naresh Boddepalli: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing—original draft; writing—review and editing. **Arti Singh**: Conceptualization; funding acquisition; project administration; resources; supervision; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

This work was supported by funding from the United States Department of Agriculture—National Institute of Food and Agriculture (USDA-NIFA) under mungbean breeding #2022–67013-37120, #2026-67013-45812, the RF Baker Center for Plant Breeding, and the Department of Agronomy. Additional support was provided by the United States Department of Agriculture Hatch CRIS project IOW04714.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data collected during this study and used in the analysis are available as supplementary material and can also be obtained from the corresponding author upon request.

ORCID

Venkata Naresh Boddepalli https://orcid.org/0009-0008-0216-9156
Arti Singh https://orcid.org/0000-0001-6191-9238

REFERENCES

Acosta-Quezada, P. G., Riofrío-Cuenca, T., Rojas, J., Vilanova, S., Plazas, M., & Prohens, J. (2016). Phenological growth stages of tree tomato (*Solanum betaceum* Cav.), an emerging fruit crop, according to the basic and extended BBCH scales. *Scientia Horticulturae*, *199*, 216–223. https://doi.org/10.1016/j.scienta.2015.12.045

Awachare, C. M., & Upreti, K. K. (2020). Phenological growth stages in mangosteen (*Garcinia mangostana* L.) according to the extended BBCH scale. *Annals of Applied Biology*, *176*, 16–25.

Bangar, P., Chaudhury, A., Tiwari, B., Kumar, S., Kumari, R., & Bhat, K. V. (2019). Morphophysiological and biochemical response of mungbean [*Vigna radiata* (L.) Wilczek] varieties at different developmental stages under drought stress. *Turkish Journal of Biology*, *43*, 58–69. https://doi.org/10.3906/biy-1801-64

Batzer, J. C., Singh, A., Platner, E., Kandel, Y., & Mueller, D. S. (2022). Screening Mungbean accessions for susceptibility to soybean fungal diseases in Iowa. *Plant Health Progress*, *23*, 456–465. https://doi.org/10.1094/php-03-22-0026-rs

Batzer, J. C., Singh, A., Rairdin, A., Chiteri, K., & Mueller, D. S. (2022). Mungbean: A preview of disease management challenges for an alternative U.S. cash crop. *Journal of Integrated Pest Management*, *13*, 4. https://doi.org/10.1093/jipm/pmab044

Bhardwaj, R., Lone, J. K., Pandey, R., Mondal, N., Dhandapani, R., Meena, S. K., Khan, S., & Gayacharan (2023). Insights into morphological and physio-biochemical adaptive responses in mungbean (*Vigna radiata* L.) under heat stress. *Frontiers in Genetics*, *14*, 1206451. https://doi.org/10.3389/fgene.2023.1206451

Cavalcante, A. G., Lemos, L. B., Meirelles, F. C., Cavalcante, A. C. P., & de Aquino, L. A. (2020). Thermal sum and phenological descriptions of growth stages of the common bean according to the BBCH scale. *Annals of Applied Biology*, *176*, 342–349. https://doi.org/10.1111/aab.12571

Dambreville, A., Lauri, P.-É., Normand, F., & Guédon, Y. (2015). Analysing growth and development of plants jointly using developmental growth stages. *Annals of Botany*, *115*, 93–105. https://doi.org/10.1093/aob/mcu227

Dhillon, A. (2020). Effect of temperature on mungbeangrowth rate. *The Expedition*, *10*. https://ojs.library.ubc.ca/index.php/expedition/article/view/195721

Douyon, A., Worou, O. N., Diama, A., Badolo, F., Denou, R. K., Touré, S., Sidibé, A., Nebie, B., & Tabo, R. (2022). Impact of crop diversification on household food and nutrition security in southern and central Mali. *Frontiers in Sustainable food Systems*, *5*, 751349.

Fotouo Makouate, H., & Zude-Sasse, M. (2025). Advances in growing degree days models for flowering to harvest: Optimizing crop management with methods of precision horticulture—A review. *Horticulturae*, *11*, 1415. https://doi.org/10.3390/horticulturae11121415

Grimes, S. J., Baier, C., Hartung, J., Longin, C. F. H., & Graeff-Hönninger, S. (2025). Phenological growth stages of common buckwheat (*Fagopyrum esculentum* Moench): An extended BBCH scale. *Journal für Kulturpflanzen*, *77*, 89–100. https://www.researchgate.net/profile/Samantha-Grimes-2/publication/394268221_Phenological_growth_stages_of_common_buckwheat_Fagopyrum_esculentum_Moench_An_extended_BBCH_scale/links/689071c858199117bcaa2b24/Phenological-growth-stages-of-common-buckwheat-Fagopyrum-esculentum-Moench-An-extended-BBCH-scale.pdf

Hack, H., Bleiholder, H., Buhr, L., Meier, U., Schnock-Fricke, U., & Weber, E. (1992). Einheitliche Codierung der phänologischen Entwicklungsstadien mono- und dikotyler Pflanzen-Erweiterte BBCH-Skala. *Allgemein. Nachrichtenblatt des Deutschen Pflanzenschutzdienstes*, *44*, 265–270.

HanumanthaRao, B., Nair, R. M., & Nayyar, H. (2016). Salinity and high temperature tolerance in Mungbean [*Vigna radiata* (L.) Wilczek] from a physiological perspective. *Frontiers in Plant Science*, *7*, 957. https://doi.org/10.3389/fpls.2016.00957

Heidt, E. E. (2024). *Disease and insect management strategies for Iowa grown mungbean (Vigna radiata)*. Iowa State University.

Herraiz, F. J., Vilanova, S., Plazas, M., Gramazio, P., Andújar, I., Rodríguez-Burruezo, A., Fita, A., Anderson, G. J., & Prohens, J. (2015). Phenological growth stages pepino (*Solanum muricatum*) according BBCH scale. *Scientia Horticulturae*, *183*, 1–7.

Herzmann, D. (n.d.). *IEM :: Agricultural weather/climate information*. https://mesonet.agron.iastate.edu/agweather/

Islam, M. R., Kamal, Mohd. M., Alam, M. A., Hossain, J., Soufan, W., Skalicky, M., Brestic, M., Habib-ur-Rahman, M., EL Sabagh, A., & Islam, M. S. (2021). Physiochemical changes of mung bean [*Vigna radiata* (L.) R. Wilczek] in responses to varying irrigation regimes. *Horticulturae*, *7*(12), 565. https://doi.org/10.3390/horticulturae7120565

Jaya, I. K. D., Sudirman, & Sudika, I. W. (2021). Mungbeancover crop improved soil organic carbon and maize yield in a semiarid area. *IOP Conference Series: Earth and Environmental Science*, *637*, 012006. https://doi.org/10.1088/1755-1315/637/1/012006

Kaur, R., Bains, T. S., Bindumadhava, H., & Nayyar, H. (2015). Responses of mungbean (*Vigna radiata* L.) genotypes to heat stress: Effects on reproductive biology, leaf function and yield traits. *Scientia Horticulturae*, *197*, 527–541. https://doi.org/10.1016/j.scienta.2015.10.015

Kebede, E. (2021). Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. *Frontiers in Sustainable Food Systems*, *5*, Article 767998. https://doi.org/10.3389/fsufs.2021.767998

Kishore, K., & Mahanti, K. K. (2016). Codification description phenological growth stages sapota (*Manilkara zapota*) according extended BBCH scale. *Scientia Horticulturae*, *211*, 431–439.

Koyejo, A. O., Okpara, D. A., & Agugo, B. A. C. (2021). Effect of alley cropping on soil, maize and mungbean grown under different maize spatial arrangements and mungbean spacings in south east Nigeria. *Agroforestry Systems*, *97*, 1337–1346. https://doi.org/10.1007/s10457-021-00635-5

Langyan, S., Yadava, P., Khan, F. N., Dar, Z. A., Singh, R., & Kumar, A. (2022). Sustaining protein nutrition through plant-based foods. *Frontiers in Nutrition*, *8*, 772573.

Liang, J., He, Z., & Shi, W. (2020). Cotton/mungbeanintercropping improves crop productivity, water use efficiency, nitrogen uptake,

and economic benefits in the arid area of Northwest China. *Agricultural Water Management*, *240*, 106277. https://www.sciencedirect.com/science/article/pii/S0378377420301402

Lisciani, S., Marconi, S., Le Donne, C., Camilli, E., Aguzzi, A., Gabrielli, P., Gambelli, L., Kunert, K., Marais, D., Vorster, B. J., Alvarado-Ramos, K., Reboul, E., Cominelli, E., Preite, C., Sparvoli, F., Losa, A., Sala, T., Botha, A.-M., & Ferrari, M. (2024). Legumes and common beans in sustainable diets: Nutritional quality, environmental benefits, spread and use in food preparations. *Frontiers in Nutrition*, *11*, 1385232.

Liu, K., Li, H., Yuan, C., Huang, Y., Chen, Y., & Liu, J. (2015). Identification of phenological growth stages of sugar apple (*Annona squamosa* L.) using the extended BBCH-scale. *Scientia Horticulturae*, *181*, 76–80. https://doi.org/10.1016/j.scienta.2014.10.046

Liu, Y., Diao, C., & Yang, Z. (2023). CropSow: An integrative remotely sensed crop modeling framework for field-level crop planting date estimation. *ISPRS Journal of Photogrammetry and Remote Sensing*, *202*, 334–355.

Malaviarachchi, M. A. P. W. K., De Costa, W. A. J. M., Kumara, J. B. D. A. P., Suriyagoda, L. D. B., & Fonseka, R. M. (2016). Response of mungbean(*Vigna radiata* (L.) R. Wilczek) to an increasing natural temperature gradient under different crop management systems. *Journal of Agronomy and Crop Science*, *202*, 51–68. https://doi.org/10.1111/jac.12131

Martínez, R., Legua, P., Martínez-Nicolás, J. J., & Melgarejo, P. (2019). Phenological growth stages of "Pero de Cehegín" (*Malus domestica* Borkh): Codification and description according to the BBCH scale. *Scientia Horticulturae*, *246*, 826–834. https://doi.org/10.1016/j.scienta.2018.11.067

McMaster, G. S., & Wilhelm, W. W. (1997). Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology*, *87*, 291–300.

Meier, U. (2018). *Growth stages of mono- and dicotyledonous plants: BBCH monograph*. https://doi.org/10.5073/20180906-074619

Mendes, D. S., Pereira, M. C. T., Nietsche, S., Silva, J. F., Rocha, J. S., Mendes, A. H., Xavier, H. R. A., & Santos, R. C. D. O. S. (2017). Phenological characterization and temperature requirements of *Annona squamosa* L. in the Brazilian semiarid region. *Anais da Academia Brasileira de Ciências*, *89*, 2293–2304. https://doi.org/10.1590/0001-3765201720170205

Mesfin, S., Gebresamuel, G., Haile, M., & Zenebe, A. (2023). Potentials of legumes rotation on yield and nitrogen uptake of subsequent wheat crop in northern Ethiopia. *Heliyon*, *9*, e16126. https://doi.org/10.1016/j.heliyon.2023.e16126

Nair, R., & Schreinemachers, P. (2020). Global status and economic importance of mungbean. In R. Nair, R. Schafleitner, & S. H. Lee (Eds.), *The mungbean genome* (pp. 1–8). Springer.

Nxumalo, G. S., Ramabulana, T. S., Dlamini, Z., Louis, A., & Nagy, A. (2026). Integrating OPTRAM and machine learning with multimodal EO proxies for optimized irrigation scheduling in smallholder systems: A Vhembe District case study. *Frontiers in Agronomy*, *7*, 1697188. https://doi.org/10.3389/fagro.2025.1697188

Oluwole, O., Ibidapo, O., Arowosola, T., Raji, F., Zandonadi, R. P., Alasqah, I., Lho, L. H., Han, H., & Raposo, A. (2023). Sustainable transformation agenda for enhanced global food and nutrition security: A narrative review. *Frontiers in Nutrition*, *10*, 1226538.

Pati, K., Kaliyappan, R., Chauhan, V. B. S., Bansode, V., Nedunchezhiyan, M., Hegde, V., & Koundinya, A. V. V. (2020). Phenological growth stages of underutilised crop yam bean (*Pachyrhizus erosus*L. Urban) according to the extended BBCH scale. *Annals of Applied Biology*, *177*, 417–423. https://doi.org/10.1111/aab.12637

Pinzón-Sandoval, E. H., Carvalho Silva, W., & Marchiori, P. E. R. (2024). Phenology, mass accumulation patterns and growing degree days in common bean. *Revista de ciencias agrícolas*, *41*, e3239. https://doi.org/10.22267/rcia.20244103.239

Pookpakdi, A., Promkham, V., Chuangpetchinda, C., Pongkao, S., Lairungreang, C., & Tawornsuk, C. (1992). Growth stage identification in mungbean (*Vigna radiata* (L.) Wilczek). *Agriculture and Natural Resources*, *26*, 75–80. https://li01.tci-thaijo.org/index.php/anres/article/view/241757

Ramírez, F., & Kallarackal, J. (2018). Phenological growth stages of Feijoa [*Acca sellowiana* (O. Berg) Burret] according to the BBCH scale under tropical Andean conditions. *Scientia Horticulturae*, *232*, 184–190. https://doi.org/10.1016/j.scienta.2017.12.059

Ritchie, H., Rodés-Guirao, L., Mathieu, E., Gerber, M., Ortiz-Ospina, E., Hasell, J., & Roser, M. (2023). *Population growth*. OurWorldinData.org. https://ourworldindata.org/population-growth

Rocha, L. G., Masetto, T. E., Araújo, R. M., Silva, D. M., & Toledo, M. Z. (2025). Seed development of mung bean: An approach of maturation in tropical conditions. *Brazilian Journal of Biology*, *85*, e297665. https://doi.org/10.1590/1519-6984.297665

Samal, I., Bhoi, T. K., Raj, M. N., Majhi, P. K., Murmu, S., Pradhan, A. K., Kumar, D., Paschapur, A. U., Joshi, D. C., & Guru, P. N. (2023). Underutilized legumes: Nutrient status and advanced breeding approaches for qualitative and quantitative enhancement. *Frontiers in Nutrition*, *10*, 1110750.

Sandhu, K., & Singh, A. (2021). Strategies for the utilization of the USDA mungbeangermplasm collection for breeding outcomes. *Crop Science*, *61*, 422–442. https://doi.org/10.1002/csc2.20322

Schieler, M., Riemer, N., Kleinhenz, B., Saucke, H., Veith, M., & Racca, P. (2023). SIMONTO-pea: Phenological models to predict crop growth stages in BBCH of grain and green peas (*Pisum sativum*) for temporal pest management. *Agriculture*, *14*, 15. https://doi.org/10.3390/agriculture14010015

Somta, P., Laosatit, K., Yuan, X., & Chen, X. (2022). Thirty years of mungbean genome research: Where do we stand and what have we learned? *Frontiers in Plant Science*, *13*, 944721. https://doi.org/10.3389/fpls.2022.944721

Sosa-Zuniga, V., Brito, V., Fuentes, F., & Steinfort, U. (2017). Phenological growth stages of quinoa (*Chenopodium quinoa*) based on the BBCH scale. *Annals of Applied Biology*, *171*, 117–124. https://doi.org/10.1111/aab.12358

Taghavi, T., Rahemi, A., & Suarez, E. (2022). Development of a uniform phenology scale (BBCH) in hazelnuts. *Scientia Horticulturae*, *296*, 110837. https://www.sciencedirect.com/science/article/pii/S0304423821009444

USDA Natural Resources Conservation Service. (2024). *MungbeanCover crop fact sheet*. United States Department of Agriculture. https://www.nrcs.usda.gov/sites/default/files/2024-07/Mung%20Bean%20Cover%20Crop%20Fact%20Sheet.pdf

Viroli, G., Kalmpourtzidou, A., & Cena, H. (2023). Exploring benefits and barriers of plant-based diets: Health, environmental impact, food accessibility and acceptability. *Nutrients*, *15*, 4723. https://doi.org/10.3390/nu15224723

Wang, X., Hua, J., Kang, M., Wang, H., & de Reffye, P. (2024). Functional-structural plant model "GreenLab": A state-of-the-art review. *Plant Phenomics*, *6*, 0118. https://doi.org/10.34133/plantphenomics.0118

Wilbur, J., do Granja, M. O., Lysek, L., Beers, E. P., Wilkinson, C., Rosso, M. L., Zhang, B., & Abaye, A. O. (2025). Evaluating Mungbean (*Vigna radiata*) as an alternative specialty crop for Virginia tobacco farmers. *Legume Science*, *7*, e70054. https://doi.org/10.1002/leg3.70054

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., Xia, L., Shen, Y., Pacenka, S., Steenhuis, T. S., Siddique, K. H. M., Kang, S., & Butterbach-Bahl, K. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. *Nature Communications*, *15*, 198.

You, Y., Tian, H., Pan, S., Shi, H., Bian, Z., Gurgel, A., Huang, Y., Kicklighter, D., Liang, X.-Z., Lu, C., Melillo, J., Miao, R., Pan, N., Reilly, J., Ren, W., Xu, R., Yang, J., Yu, Q., & Zhang, J. (2022). Incorporating dynamic crop growth processes and management practices into a terrestrial biosphere model for simulating crop production in the United States: Toward a unified modeling framework. *Agricultural and Forest Meteorology*, *325*, 109144.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Boddepalli, V. N., & Singh, A. (2026). Defining the growth stages of mungbean (*Vigna radiata* L.) using the BBCH scale. *Agronomy Journal*, *118*, e70448. https://doi.org/10.1002/agj2.70448