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Effect of Sowing Time on the Growth of Mungbean (*Vigna radiata* L.) Genotypes Within Temperate Environments of Southern Australia

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ABSTRACT

Mungbean is predominantly cultivated within a subtropical climate, and its potential for cultivation in temperate regions as a summer crop has not been comprehensively assessed. This research investigates the influence of temperature and seasonal variation with sowing time on mungbean phenology, growth and yield at five locations within the temperate environment of southeastern Australia (Victoria). Five mungbean varieties (Jade-AU, Celera II-AU, Golden Dragon, Putland and Crystal) were evaluated across two times of sowing (TOS) (spring and early summer) over 2 years (2020–2021 and 2021–2022 summers) at sites in southwestern (Hamilton and Horsham), northeastern (Rutherglen) and northwestern (Ouyen and Woomelang) Victoria. These locations are characterised by winter-dominant rainfall patterns with sporadic summer rainfall events, which can be significant. Annual rainfall varied across sites: low rainfall (< 350 mm, Ouyen and Woomelang), medium rainfall (350–450 mm, Horsham) and high rainfall (> 350 mm, Hamilton and Rutherglen). Early sowing coincided with lower soil temperatures, leading to delayed emergence and reduced establishment. However, TOS did not significantly influence grain yield, except at Rutherglen (TOS 1, 715 kg/ha; TOS 2, 1576 kg/ha). Grain yield was correlated with grain number and biomass, significantly contributing to variations in yield. The variety Jade-AU exhibited superior performance in low and medium rainfall regions in Victoria, whereas Putland and Crystal varieties demonstrated optimal performance in high rainfall zones. Under dryland cropping conditions, northeastern Victoria (e.g., Rutherglen) may represent the most promising opportunity for mungbean cultivation. Nevertheless, when selecting varieties for summer mungbean cultivation in southern Australia, it is imperative to consider differences in days to first flowering, yield potential, heat stress tolerance and rainfall patterns.

1 | Introduction

Mungbean (*Vigna radiata* (L.) Wilczek) is a short-duration crop that is predominantly grown in subtropical areas of Asia for its protein-rich seeds. Globally, mungbean production is approximately 5.3 million tonnes from a total cultivation area of 7.3 million hectares (Ademe 2023). Mungbean is considered an important crop in double and intercropping systems between two cereal crops due to its short growing period (60–110 days) (Gentry 2010). In Australia, mungbean is a major summer legume crop that can be grown on diverse soil types (Grains Research and Development Corporation 2017; Australian Mungbean

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Association 2021b), with total grain production of 90,000 tonnes per annum (Australian Mungbean Association 2021b). The crop is primarily grown under a warm-humid climate with a temperature range of 25°C–35°C and growing season rainfall of 400–550 mm (Bhardwaj et al. 2023; Gayacharan et al. 2023). In Australia, mungbean is mainly produced in central and southern Queensland and northern New South Wales, with some additional production in the northern coastal region of the Northern Territory. In these regions, mungbean provides a high-value crop with Australian prices averaging AUS$1000–1200 per tonne in 2023 (Wells 2023), making it a financially viable crop for farmers seeking crop diversification.

Within Australia, there is the potential to increase mungbean production to meet increasing global demand. In addition to increasing production within current regions by optimising agronomic practices and adaptation (breeding), there is also the potential to expand into new regions. One potential area for expansion is southern Australia, as an opportunistic summer crop to fit in rotation with winter crops (e.g., wheat and canola) or after a failed winter crop where the land is otherwise left fallow until April–June for the next crop. Mungbean, with a short growing period, may fit into the summer cropping window and benefit growers by creating new cropping opportunities, providing an alternative crop for Victorian farmers, fixing soil nitrogen and increasing on-farm biodiversity.

Early vigour is a crucial trait that impacts the establishment of mungbean, as uniform establishment is vital for successful mungbean production (Rachaputi et al. 2015). The germination rate of plants affects emergence and establishment. For optimal germination, mungbean requires a temperature of 30°C–40°C to achieve the rapid emergence (Fyfield and Gregory 1989) necessary to meet the target of 30 plants/m^2 (Rachaputi et al. 2015). Soil temperatures in Queensland and northern New South Wales, where mungbean is grown in subtropical areas, remain above 25°C during the sowing window from October to December (Delahunty et al. 2020). In contrast, southern Australia experiences lower temperatures, averaging below 20°C from October to November (Christy et al. 2022). These lower soil temperatures during early spring can significantly influence mungbean establishment, with cooler conditions impeding germination, resulting in slower emergence and uneven establishment, leading to reduced yield (Hussain and Khalil 2004; Tzudir et al. 2014). Understanding these temperature dynamics is crucial, as they directly influence the advantageous air temperatures and photoperiods that promote rapid canopy development during the vegetative growth stage, resulting in increased dry matter production (McKenzie et al. 1992).

Air temperature during mungbean cultivation is a significant factor affecting growth and development. Australian mungbean varieties are sensitive to temperature, with optimal growth occurring at air temperatures between 28°C and 30°C (Poehlman 1991; Chauhan and Williams 2018). Lower temperatures delay crop growth and development, resulting in delayed maturity. Mungbean requires 600 growing degree days (GDDs) for flowering and 1200 GDDs for maturity under the subtropical conditions typical of Queensland (Chauhan and Rachaputi 2014); however, the days to flowering and maturity may vary for southern conditions. Exposure to cold conditions later in the maturing phase during March–April can delay physiological maturity after grain set, as mungbean transitions from flowering to grain filling to physiological maturity based on thermal time (Chauhan and Williams 2018). Additionally, a lower temperature of 12°C during flowering and pod filling for 5 days could decrease mungbean yield by up to 50% (Xiang et al. 2023). Mungbean is sensitive to low temperatures; exposure to low temperatures in early growth stages affects its productivity. Mungbean seedlings exposed to 4°C for 2 days can experience irreversible damage to cells; however, acclimation at 10°C can result in less damage (Chang et al. 2001; Miura and Furumoto 2013). More understanding of abiotic factors limiting the adaptation of mungbean is essential for integrating this crop into the southern Australian farming systems.

Photoperiod, along with temperature, significantly influences mungbean growth and development, making it a critical factor to consider for opportunistic summer cropping in southern Australia. Mungbean is a short-day plant and its phenological development relies on temperature and photoperiod (Bashandi and Poehlman 1974; Chauhan and Williams 2018). Longer photoperiods delay flowering in short-day plants (Xue et al. 2024). In southern Australia, the average day length is longer during summer and shorter in winter compared to northern Australia because of latitude. For example, the summer maximum average day length for Horsham, Victoria, in southern Australia is around 15.7 h (at summer solstice) compared to 14.4 h (e.g., Emerald, Queensland) in the current production regions of northern Australia (Time and Date AS 2024). Most mungbean genotypes are photo-sensitive, thriving under a photoperiod range of 12–16 h (Lawn 1979; Chauhan and Williams 2018). They are more sensitive to photoperiods under higher temperatures in certain varieties that can delay flowering when exposed to longer photoperiods exceeding 14 h (Rawson and Craven 1979; Imrie and Lawn 1990). Therefore, the response of photoperiod on mungbean in temperate regions of southern Australia needs to be explored to better understand adaptation opportunities in these farming systems.

Adequate rainfall and soil water availability are critical factors that influence the successful integration of mungbean cultivation in southern Australia. Mungbean requires 350–400 mm of water during the growing season to achieve maximum yield potential in the subtropical areas of Australia (Grains Research and Development Corporation 2017). The amount of stored soil water at sowing time following the winter cropping cycle in southern Australia is highly variable, and summer rainfall for crop growth and development is largely unpredictable (Thomas and Fukai 2001). This leads to significant variability in grain productivity and quality. Although the advantage of mungbean is its relative drought tolerance and its ability to grow under rainfed conditions (Dutta and Bera 2008; Ahmad et al. 2015), it is often sown in low soil water (90-mm plant-available water) with in-crop rain of less than 150 mm (Wenham et al. 2020), resulting in drought stress. A desktop study by Christy et al. (2022) indicated that the likelihood of a successful crop without supplementary irrigation in southern Australia ranged from 29% to 65%, based on requiring 5-day rainfall exceeding 30 mm between October and December for sowing and 150 mm of rainfall within 90 days after sowing (DAS) for a successful crop. Mungbean response to drought depends on crop growth stage,

stress duration and variety (Bangar et al. 2019). For example, Wenham et al. (2020) reported on the impact of water availability during different growth stages (plants were not watered until soil water dropped below 40% of field capacity), where drought stress during the vegetative stage of mungbean decreased yield by 10%–33%, whereas during flowering, the yield decrease was 5%–27%, and during early pod filling period, yield decreased by 53%–75% compared to nonstress crops. In southern Australia, where the chance of follow-up rainfall is lower, it is crucial to evaluate stored water reserves before sowing in order to avoid drought stress, as mungbean tends to experience terminal water stress during critical growth stages.

Aligning the timing and duration of crucial growth phases with anticipated and forecasted seasonal conditions represents a vital strategy for enhancing adaptation and productivity across diverse environments by optimising water utilisation during key growth stages. Agronomic strategies, including adjusting sowing time and seeding rates, adopting effective irrigation methods and managing soil and weeds, represent viable means to mitigate the impacts of water stress and improve crop productivity.

The goal is to assess the feasibility of cultivating mungbean as an opportunistic summer crop in southern Australia. This study aims to investigate how sowing time and the resulting variations in the growing season affect mungbean growth by examining its phenology and yield potential.

2 | Materials and Methods

2.1 | Site Description and Weather

The experiments were conducted during summers 2020–2021 (trial year 2020) and 2021–2022 (trial year 2021) at sites in Ouyen, Woomelang, Horsham, Rutherglen and Hamilton, located in Victoria, Australia, to investigate the effects of time of sowing (TOS) and associated differences in the growing season window on crop growth. Each trial included two TOS and three replicates. Trials were located at Ouyen (35°00′32″ S latitude, 142°15′00″ E longitude; 52 m above sea level [masl]); Woomelang (35°45′49″ S latitude, 142°30′08″ E longitude; 85 masl); Horsham (36°44′57″ S latitude, 142°06′59″ E longitude; 128 masl); Hamilton (37°49′38″ S latitude, 142°04′12″ E longitude; 207 masl); and Rutherglen (36°06′28.2″ S latitude, 146°31′08.2″ E longitude; 177 masl) (Figure 1). According to the Köppen climate classification system, the sites can be classified as (i) cold semi-arid climate (BSk)—Ouyen, Woomelang and Horsham; (ii) cool oceanic climate (Cfb)—Hamilton; and (iii) humid subtropical climate (Cfa)—Rutherglen. In these regions, summer occurs between December and February, whereas from June to September, it is cold and wet. Long-term average annual rainfall is 330, 348, 378, 619 and 588 mm for Ouyen, Woomelang, Horsham, Hamilton and Rutherglen, respectively. Experimental site details including soil type, total in-crop rainfall and sowing dates for each site are described in Table 1. Soil temperature at a depth of 10 cm was measured daily using a Tinytag temperature probe (Tinytag Plus 2–TGP-4510, Australia). Data on maximum and minimum air temperatures and rainfall were obtained from the Australian Bureau of Meteorology (Bureau of Meteorology 2023).

2.2 | Experimental Design

The experiment at each site used a split-plot design with three replicates (Gomez and Gomez 1984). The two TOS were assigned as main plots and varieties (Table 1) were assigned as subplots. Five commercial mungbean varieties (Jade-AU, Celera II-AU, Golden Dragon, Putland and Crystal) with contrasting seed and growth characteristics (Table 2) were tested at different combinations across Ouyen, Woomelang, Horsham, Hamilton and Rutherglen over 2 years, except at Hamilton where the varieties were not tested in 2020 (Table 1) due to pest damage. The selection of varieties at each site and year depended on seed availability. Jade-AU and Celera II-AU were used as checks across sites and years. The varieties Jade-AU, Celera II-AU, Putland and Crystal are commercial varieties targeted for central and southern Queensland and northern New South Wales, whereas Golden Dragon is a non-commercial variety targeted for the specialty market. All the seeds for tested varieties were obtained from the Australian Mungbean Association, Australia, except Golden Dragon, which was obtained from Unicorn Specialty Foods, Australia.

2.3 | Crop Management

The trials were sown using a tractor-mounted, plot-scale seeder equipped with narrow-point tynes and press wheels, at a rate of 1–1.2 kg/ha to achieve a target plant density of 35 plants/m^2. The size of the plots was 3 m in length and four rows in breadth spaced at 0.28, 0.30, 0.38, 0.30 and 0.23 m at Ouyen, Woomelang, Horsham, Hamilton and Rutherglen, respectively, based on local seeding equipment. The areas were 0.56, 0.60, 0.76, 0.60 and 0.46 m^2. The seeds were sown to a depth of 0.03 m. Prior to sowing, mungbean seeds were inoculated with a peat-based rhizobia inoculant (NoduleN Group I, New-Edge Microbials, Australia) at a rate of 5 g/kg of seed.

Supplemental irrigation was applied to maintain the base water supply for crops at low and medium rainfall sites, which represents an 'opportunistic year'. At Ouyen, Woomelang and Horsham, 100 mm of supplemental irrigation was applied in 2020, including 20 mm of supplemental irrigation at sowing. In contrast, in 2021, only 20 mm of supplemental irrigation was applied during sowing at these sites. In addition to in-crop supplemental irrigation, 60 and 43 mm of water were also applied in Ouyen and Woomelang about 1–2 weeks prior to the sowing date to mimic the 'opportunistic year' (Table 1). The irrigation was applied using a drip system by Netafim Streamline Model 22060, with an emitter flow rate of 1.6 L/ha, emitter spacing of 20 cm and four drip lines per plot.

The trial site was fertilised with a basal application of monoammonium phosphate (MAP) at a rate of 50 kg/ha (5.5:11:0 kg NPK/ha) and 80 kg/ha (8.8:17.6:0 kg NPK/ha), with rates aligned to industry standard for each region (based on winter pulse values). Weeds were controlled using commercial herbicides, including glyphosate, carfentrazone-ethyl and trifluralin, at label rates and timings. Similarly, insecticides, including chlorpyrifos and bifenthrin, were applied to control insect pests. Intensive manual weeding was also undertaken on two occasions each year to control weeds not removed by herbicides.

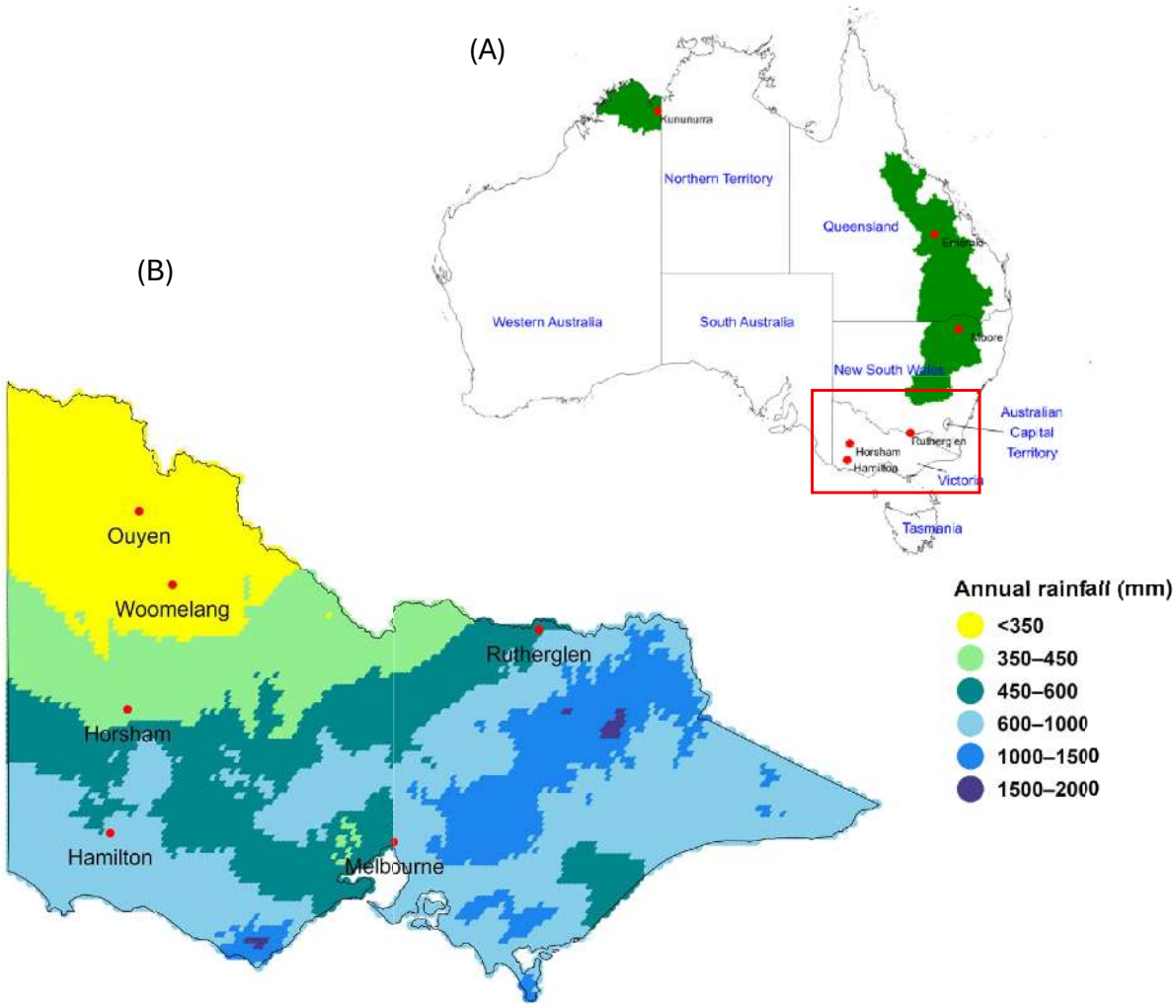


FIGURE 1 | (A) The Australian map showing mungbean-growing regions in green colour and the state of Victoria as a red inset (Australian Mungbean Association 2021a). The Australian states and territories are identified by boundaries indicated with black lines and labelled in a blue font. (B) Average annual rainfall in Victoria, 30-year climatology (1991–2020) (Bureau of Meteorology 2021). Within Victoria, there are three major cropping zones, which are characterised by rainfall: low rainfall zone (Ouyen and Woomelang) < 350 mm, medium rainfall zone 350–450 mm (Horsham) and high rainfall zone > 450 mm (Hamilton and Rutherglen).

2.4 | Data Collection

2.4.1 | Emergence Count

The number of plants that emerged (emergence of cotyledons above the soil surface) was recorded from each plot. In a plot, two middle rows of 1-m length at the centre of the row were selected for emergence count.

Median emergence time (t_{50}) is the time to reach 50% of maximum emergence and was adapted and computed according to Coolbear et al. (1984) as follows. The median emergence time is expressed as days.

$$t_{50} = t_i + \left[\frac{(N+1)/2 - n_i}{n_j - n_i}\right].(t_j - t_i)$$

where N is the final number of seeds emerging from the ground and n_i are n_j are the total number of seeds emerged by adjacent counts at time t_i, t_j, where $n_i < (N+1)/2 < n_j$.

2.4.2 | Phenology

Flowering dates were recorded when the first flowering was observed in a plot, and the trait is presented as the number of DAS as days to first flowering (DTFF). The podding date was also recorded when the first pod set was observed in a plot.

The number of days to maturity from sowing was recorded when 90% of pods were mature.

2.4.3 | Quality Traits

The seed grain weight, protein % and seed coat brightness of variety Jade-AU were measured at the Crop Quality Laboratory at Agriculture Victoria, Horsham, Australia. The protein % was determined by near-infrared spectroscopy (Foss XDS rapid Content Analyser, FOSS Analytical A/S) (Walker and Panozzo 2023). Seed coat brightness was quantified using a

TABLE 1 | Supplemental irrigation and in-season rainfall (millimetres) measured from sowing until median date of harvest, date of sowing (TOS), soil type and varieties tested at experimental sites in summers 2020 and 2021. For varieties: 1 = Jade-AU, 2 = Celera II-AU, 3 = Golden Dragon, 4 = Putland and 5 = Crystal.

Site	Year	Total irrigation (mm)		In-season rainfall (mm)	Sowing date		Harvest date[b]		Soil type[c]	Varieties
		TOS 1	TOS 2		TOS 1	TOS 2	TOS 1	TOS 2		
Ouyen	2020	100	100	52	2020/11/03	2020/12/02	2021/02/25	2021/04/09	Calcarosol	1, 2, 3, 4, 5
	2021	60[a], 20	60[a], 20	119	2021/10/08	2021/11/04	2022/03/07	2022/03/04		1, 2, 3, 5
Woomelang	2020	100	100	24	2020/11/04	2020/12/03	2021/03/10	2021/04/21	Calcarosol	1, 2, 3, 4, 5
	2021	43[a], 20	43[a], 20	113	2021/10/12	2021/11/12	2022/02/17	2022/02/24		1, 2, 3, 5
Horsham	2020	100	100	88	2020/11/05	2020/12/02	2021/03/31	2022/04/30	Vertosol	1, 2, 3, 4, 5
	2021	20	20	164	2021/10/13	2021/11/19	2022/04/17	2022/04/28		1, 2, 4, 5
Hamilton	2021	0	0	159	2021/11/12	2021/12/22	2022/04/08	2022/04/21	Chromosol	1, 2, 4
Rutherglen	2020	0	0	233	2020/11/09	2020/12/17	2021/03/10	2021/04/16	Chromosol	1, 2, 3, 4, 5
	2021	0	0	374	2021/09/28	2021/10/26	2022/02/28	2022/03/04		1, 2, 3, 4, 5

[a]Applied 1–2 weeks prior to sowing of TOS 1.
[b]Median.
[c]Australian Soil Classification.

TABLE 2 | Characteristics of mungbean varieties tested at Ouyen, Woomelang, Horsham, Hamilton and Rutherglen in summers 2020 and 2021.

Variety	Seed size and colour	Release year	Growth habit	Geographic adaptation	Key potential/advantage
Jade-AU	Large-seeded (74 mg), shiny green	2013	Erect, tall, open canopy	Central and southern Queensland and northern NSW	Powdery mildew resistance.
Crystal	Large-seeded (90 mg), shiny green	2008	Erect, medium height, lodging resistant	Central and southern Queensland and northern NSW	Powdery mildew resistance. Excellent grain consistency; standard for sprouting.
Celera II-AU	Small-seeded (41 mg), shiny green	2014	Compact, medium height, determinate	Central and southern Queensland and northern NSW	Grown for niche market in European and Asian countries; halo blight resistance.
Putland	Small-seeded (51 mg), shiny green	1991	Sprawling and vigorous producing large biomass	Central and southern Queensland and northern NSW	Weathering tolerance.
Golden Dragon	Small-seeded (50 mg), yellow	Not released	Indeterminate	NA	Sprouting, cooking and processing.

Source: Grains Research and Development Corporation 2017; Singh et al. 2025; Silwal et al. 2026; Unicorn Specialty Foods 2026.

Minolta spectrophotometer (CM5, Hamburg, Germany) based on the Commission Internationale de l'Éclairage (CIE) values L* (Walker and Panozzo 2023).

2.4.4 | Growth and Yield Components

Above-ground biomass was determined at podding (podding biomass) and physiological maturity (harvest biomass) by sampling the inner two rows of each row. Sampling of podding biomass was done at 52–119 DAS, and harvest biomass was done at 104–186 DAS (Table S1). The length of rows for podding biomass was 0.5 m. The harvested plants were oven dried until constant weight at 40°C. Plots were hand-harvested when the pods were mature, specifically from the two inner rows of each plot, measuring 1 m in length, and then dried at 40°C. The samples were utilised to determine shoot biomass (harvest biomass), plant height, plants per square metre, grain number (grains per square metre), grain weight and grain yield. Grain weight is defined as the weight of a single grain, which was calculated from total grain weight divided by grain number and is presented as milligrams. Grain yield was adjusted to 10% moisture content and presented as kilograms per hectare. The harvest index (HI) was calculated by using the following formula.

$$HI = \frac{Grain\ yield}{Total\ biomass} \times 100$$

2.5 | Data Analysis

Analysis of each variable was first conducted separately for each environment (where site and year [site × year] combination is defined as an environment) and, second, an analysis of a multi-environment trial (MET) to assess the overall varietal performance across all environments.

2.5.1 | Individual Environment Analysis

Within each environment, a linear mixed model (LMM) approach using the residual maximum likelihood (REML) method was employed to examine the effects of TOS, variety and their interactions at each environment (Butler et al. 2023) using ASReml-R package version 4.2.0.355 (The VSNi Team 2023). TOS and variety were treated as fixed effects, whereas replication and main plot were considered random effects. The effect of TOS was tested against the main plot error (replication × main plot) and for variety and its interaction with TOS, against the residual error of the experimental units or subplots.

Means of TOS, variety and TOS × variety from individual environment analysis were compared by using Tukey's honestly significant difference (HSD) test (Tukey 1949). The significance level was set at 5% in all comparisons. The interaction effects of each trait at each site are presented in graphs, and, where there was no interaction, the main effects only are presented.

2.5.2 | MET Analysis

The agronomic traits (podding biomass, harvest biomass, HI, grain weight, grain number and yield) were analysed using an MET analysis approach through an LMM that incorporated interactions between genotype and environmental factors. The models were fitted in ASReml-R package version 4.2.0.355 (The VSNi Team 2023) in R version 4.4.2 (Butler et al. 2023) as follows:

$$y = X\tau + Zu + e$$

In the model, X denotes the design matrix associated with a vector of fixed effects (τ), which includes environmental factors (site, year and TOS) and their interactions with variety. Conversely, Z represents the design matrix for the vector of random effects (u), which captured experimental design factors including environment, replication and main plot structure to account for field variation. To account for variance heterogeneity across environments, the residual term (e) is used. The residual error structure was modelled using a diagonal sum of variances (dsum), which allowed a unique, site-specific residual variance for each level of the environment factor, rather than assuming a single, homogeneous error across the entire MET.

The modelling process followed a sequential selection strategy. Initially, a full factorial fixed effect structure (incorporating all interactions up to the four-way site × year × TOS × variety) was maintained, whereas the competing random effect structure was refined to account for the spatial and environmental constraints of the MET (Table S2). After the sequence of refinement, a heterogenous variance structure using a diagonal covariance framework was selected based on Akaike information criterion (AIC), Bayesian information criterion (BIC) and REML log-likelihood ratio. The refinement accounted for differing levels of experimental noise at each site × year combination using the likelihood ratio test.

Subsequently, fixed effect selection was performed by comparing a full factorial model (incorporating all interactions up to the four-way site × year × TOS × variety) against a reduced model focused on primary genotype × environment (G × E) components (Table S3). The reduced model was selected based on lower AIC and BIC employing full maximum likelihood using asremlPlus version 4.4.55 in R (Verbyla 2019). Additionally, a log-likelihood ratio test (LRT) indicated no significant loss of fit compared to the full model ($p = 0.098$).

The fixed effect structure was determined based on the most complex trait (grain yield) to capture all potential interactions of site, year, TOS and variety. This consistent model structure was maintained across all agronomic traits to ensure that the reported Wald statistics and significance levels are directly comparable across the different components of mungbean productivity. Fixed effects were tested using the conditional Wald statistic to account for all other factors in the model.

Means were compared by using Tukey's HSD test (Tukey 1949). The significance level was set at 5% in all comparisons.

2.5.3 | Relationships Among Yield and Yield Attributing Traits

Correlation analysis was carried out to determine the relationships between yield and yield parameters using package

'rstatix' version 0.7.2 (Kassambara 2023) in R 4.4.2. To examine the relationships among the yield and yield attributing traits in this study, a principal component analysis (PCA) was conducted using the best linear unbiased estimates (BLUEs) from MET analysis for each genotype across the environments. The PCA was conducted using package 'factoextra' version 1.0.7 (Kassambara and Mundt 2020) in R version 4.4.2.

2.5.4 | Environmental Correlations and G×E Interactions

Predicted means (BLUE) for grain yield derived from REML analysis from each environment were used to assess environmental correlations and G×E interactions using the additive main effects and multiplicative interaction (AMMI) model (Gauch 2006):

$$Y_{ij} = \mu + G_i + E_j + \sum_{K=1}^{n} \lambda_k \alpha_{ik} \gamma_{ik} + \varepsilon_{ij}$$

where Y_{ij} is the response variable obtained from the ith genotype in the jth environment; μ is the grand mean; G_i and E_j are the genotype and environment deviations from the grand mean, respectively; λ_k is the eigenvalue of the PCA analysis axis k; α_{ik} and γ_{ik} are the genotype and environment principal component scores for axis k; n is the number of principal components retained in the model; and ε_{ij} is the error term.

These BLUEs were also utilised to characterise environments through the genotype main effects and genotype by environment interaction (GGE) model (Gauch 2006):

$$Y_{ij} - \mu - \beta_j = g_{i1} e_{1j} + g_{i2} e_{2j} + \varepsilon_{ij}$$

where g_{i1} and e_{1j} are the primary scores for genotype i and environment j, respectively; g_{i2} and e_{2j} are the secondary score for genotype i and environment j, respectively; and ε_{ij} is the residue not explained by the primary and secondary effects. A GGE biplot is constructed by plotting g_{i1} against e_{1j} and g_{i2} against e_{2j} in a single scatter plot.

To accommodate the unbalance nature of the data set, the missing values were estimated using the iterative least square procedure prior to the AMMI decomposition in GenStat 22nd edition (VSN International 2022). To account for these estimations, the error degrees of freedom were adjusted accordingly to ensure the validity of the F-tests during the AMMI decomposition. This approach aligns with the expectation–maximisation procedure described by Rodrigues et al. (2014), where missing cells are estimated to maintain the requirements of singular value decomposition while preserving the underlying interaction structure between the varieties and environments. All statistical analyses were performed by using ASReml-R package version 4.2.0.355 (The VSNi Team 2023) in R version 4.4.2, whereas AMMI and GGE decompositions were conducted in GenStat 22nd edition (VSN International 2022).

3 | Results

3.1 | Weather

Total in-season rainfall at the 2020 trial sites was 88, 52, 233 and 24 mm at Horsham, Ouyen, Rutherglen and Woomelang, respectively. In 2021, the total in-season rainfall was 159, 164, 119, 374 and 113 mm at Hamilton, Horsham, Ouyen, Rutherglen and Woomelang, respectively (Table 1).

At Ouyen, total rainfall in 2021 was greater (119 mm) compared to 2020 (52 mm). In 2020, most rainfall occurred during the vegetative stage, whereas in 2021, most of the rainfall coincided with the flowering and pod filling stages (Figure 2). At Woomelang in 2020, more water was received during the vegetative (40-mm supplemental irrigation) and reproductive stages (40-mm supplemental irrigation). In contrast, in 2021, most of the water received was within 30 days of sowing (44 mm for TOS 1 and 23 mm for TOS 2) or close to harvest (53 mm on 18 and 19 March 2022). From 1 January 2022 to 1 March 2022, there was only 4 mm of rainfall (Figure 2). No supplementary irrigation was applied at Woomelang in 2021 during the vegetative and reproductive stages. Horsham received similar amounts of water, including rainfall and supplemental irrigation, in the 2020 and 2021 trials. In 2020, Horsham received 88 mm of rainfall and 100 mm of supplemental irrigation across the sowing, vegetative and reproductive stages, whereas in 2021, 20 mm of supplemental irrigation was applied at sowing and 164 mm of rainfall during the growing season. In 2020, Rutherglen received a total of 233 mm of rainfall, which increased to 374 mm in 2021. In comparison, Hamilton recorded 159 mm of rainfall in 2021 during the growing season. No supplementary irrigation was applied at Rutherglen and Hamilton.

The average air temperature during the experiment from sowing to harvest ranged from 18.2°C to 23.1°C (Table 3). TOS 2 recorded higher mean temperatures than TOS 1 across the sites, with the exception of Horsham 2020 and Ouyen 2020. In both cases, the average air temperatures were higher at the northern site, Ouyen, and lowest at the southernmost site, Hamilton, for all the sowing treatments. The average soil temperature at sowing ranged from 11.4°C to 23.5°C. Soil temperatures at sowing were higher at TOS 2 across the sites except for Ouyen 2020.

3.2 | The Relationship Between Emergence and Soil Temperature

Correlation analysis between median emergence time (days, t_{50}) and soil temperature at sowing showed that there was a strong negative relationship between the two parameters ($r = -0.73$**, $R^2 = 0.60$) (Figure 3A), where lower soil temperature at sowing delayed emergence across the sites. For a soil temperature range between 12°C and 24°C, it was observed that with every degree Celsius increase in soil temperature, the time to 50% emergence decreased by 1 day. Here, TOS 2 had a faster emergence rate compared to TOS 1 across the sites, driven by higher soil

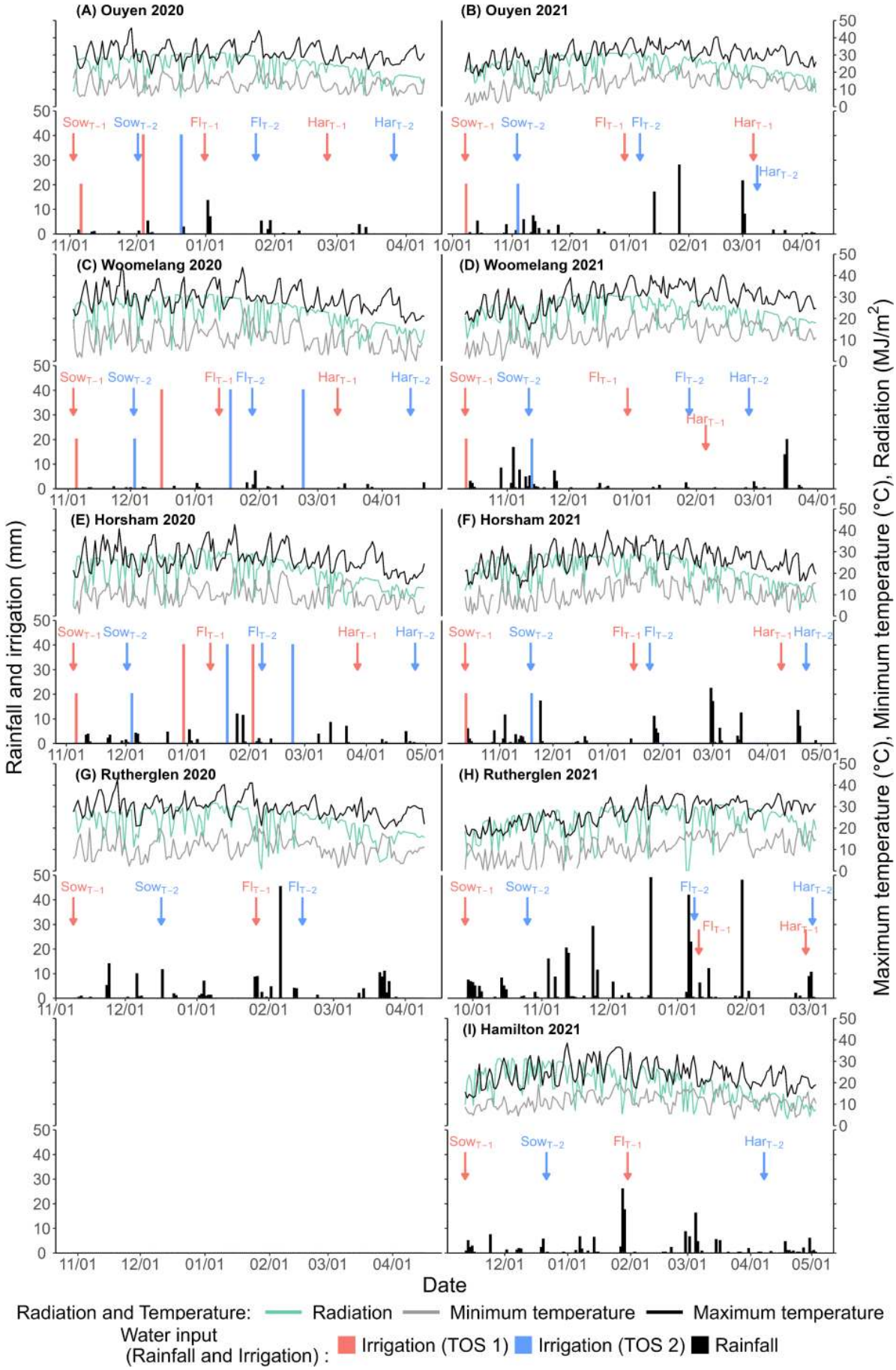


FIGURE 2 | Legend on next page.

FIGURE 2 | (A–I) Rainfall, irrigation, temperature and solar radiation at Ouyen, Woomelang, Horsham, Hamilton and Rutherglen sites during the mungbean growing period in 2020 and 2021. The 2020 season includes the summers of 2020–2021, and the 2021 season includes the summers of 2021–2022. Arrows indicate sowing, flowering and harvesting of mungbean where Sow = sowing, Fl = initiation of first flower, Har = harvesting, T-1 = TOS 1 and T-2 = TOS 2.

TABLE 3 | Average soil temperature (at 10 cm) at sowing, average air temperature (°C), average maximum air temperature (°C) and average minimum air temperature (°C) for each time of sowing (TOS) from sowing to average harvest date at Hamilton, Horsham, Ouyen, Woomelang and Rutherglen in 2020 and 2021.

Year	Site	Time of sowing (TOS)	Sowing date	Average soil temperature at sowing (°C)	Average air temperature (°C)	Average maximum air temperature (°C)	Average minimum air temperature (°C)
2020	Horsham	1	5 Nov	18.6	19.4	28.0	10.9
		2	2 Dec	19.5	18.5	26.8	10.1
	Ouyen	1	3 Nov	23.5	22.9	31.9	13.9
		2	2 Dec	22.5	22.1	30.8	13.4
	Rutherglen	1	9 Nov	NA	20.2	29.4	10.9
		2	17 Dec	NA	20.1	29.1	11.2
	Woomelang	1	4 Nov	20.2	21.1	30.4	11.8
		2	3 Dec	21.2	20.2	29.2	11.2
2021	Hamilton	1	12 Nov	15.6	18.2	24.6	11.7
		2	22 Dec	18.2	19	25.4	12.5
	Horsham	1	13 Oct	11.4	19.1	27.2	11.0
		2	19 Nov	14.6	20.1	28.3	11.9
	Ouyen	1	8 Oct	14.9	21.9	30.2	13.5
		2	4 Nov	19.7	23.1	31.3	14.9
	Rutherglen	1	28 Sep	NA	18.8	26.9	10.8
		2	26 Oct	NA	18.9	26.9	10.9
	Woomelang	1	12 Oct	13.8	20.9	29.4	12.5
		2	12 Nov	14.3	22.8	31.4	14.3

temperatures at sowing. For the median emergence time (days, t_{50}), there was a strong inverse correlation with final emergence ($r = -0.60^{**}$, $R^2 = 0.36$) (Figure 3B) and plant density (plants/m^2) at harvest ($r = -0.74^{**}$, $R^2 = 0.55$) (Figure 3C). The faster emergence rate positively influenced the higher emergence, leading to improved establishment and plant density at harvest. In contrast, TOS 2 exhibited a quicker emergence rate than TOS 1 across the sites, resulting in higher overall establishment and higher overall plant density at harvest across the sites.

3.3 | DTFF

Average DTFF ranged from 53 to 105 DAS for varieties across the TOS and trial sites (Figure 4). The average DTFF for TOS 1 and TOS 2 was 81 and 64 DAS across the trials. There was a strong negative relationship between the sowing day of the year and DTFF across sites ($r = -0.81^{***}$, $R^2 = 65$, Figure 4). The average DTFF for varieties ranged from 69 to 76 DAS across the trials, with the DTFF for the varieties Celera II-AU, Crystal, Golden Dragon, Jade-AU and Putland recorded as 73, 76, 69, 75 and 75 DAS, respectively. The average DTFF was earlier in Ouyen and Woomelang with 66 and 69 DAS, respectively, followed by Horsham (75 DAS) and Rutherglen (80 DAS). The average GDDs from sowing to start of first flowering ranged from 538 to 1195, and the average photoperiod ranged from 13.90 to 14.54 h (Table S4).

3.4 | Podding Biomass

Podding biomass was significantly influenced by variety ($W = 24.24$, $p < 0.001$), site ($W = 274.47$, $p < 0.001$) and year ($W = 26.71$, $p < 0.001$), whereas the main effect of TOS was not significant (Table 4). Significant two-way interactions

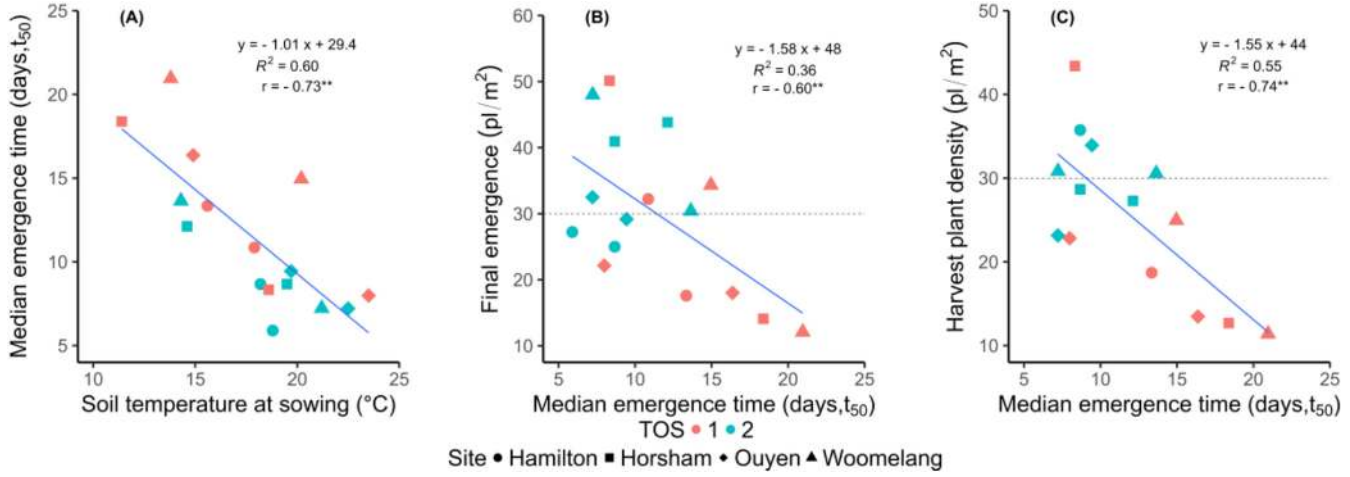


FIGURE 3 | (A) Median emergence time (t_{50}) of mungbean against the soil temperature (10 cm) at sowing, (B) final emergence (plants/m^2) against median emergence time (t_{50}) and (C) harvest plant density (plants/m^2) against median emergence time (t_{50}) of mungbean across the sites of Ouyen, Woomelang, Horsham and Hamilton in summers 2020 and 2021. Dotted line in (B) and (C) represents the threshold for the recommended plant density for mungbean cultivation.

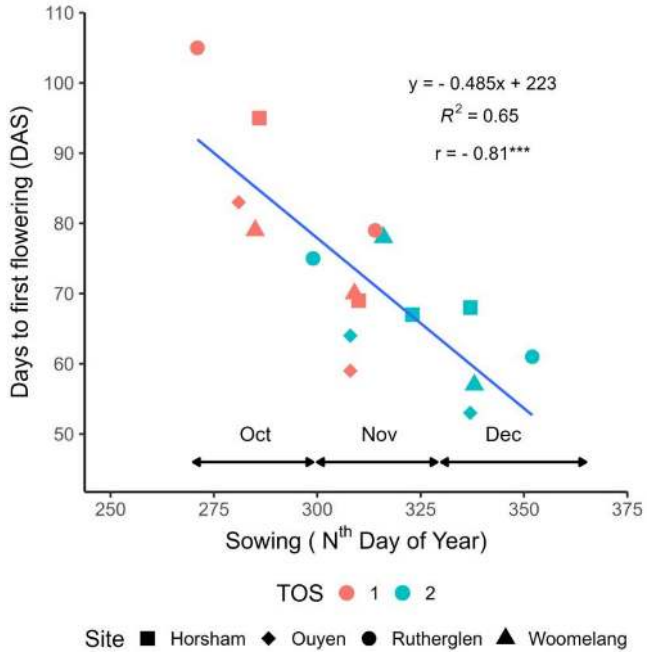


FIGURE 4 | The relationship between sowing day and days to flowering of mungbean varieties.

included site × variety (W = 11.91, $p < 0.001$), year × variety (W = 11.95, $p < 0.05$), site × year (W = 19.61, $p < 0.001$), site × TOS (W = 10.21, $p < 0.05$) and year × TOS (W = 4.84, $p < 0.05$). The overall TOS × variety interaction was not significant across environments (Table 4); however, site-specific analyses indicated that this interaction occurred in selected environments (Figure 5).

Individual environment (site × year) analyses showed that the variety effect was significant in Horsham 2020 ($p = 0.002$), Horsham 2021 ($p = 0.007$) and Ouyen 2020 ($p = 0.014$) but not significant in Hamilton 2021, Ouyen 2021, Woomelang 2020 and Woomelang 2021 (Tables 5 and S5). A significant TOS × variety interaction was observed at Horsham 2021 and Woomelang 2021 ($p < 0.05$; Figure 5 and Table S5). In contrast, no significant TOS × variety interaction was observed in the remaining environments, indicating that sowing time effects on podding biomass were generally consistent across varieties outside Horsham 2021 and Woomelang 2021. At Horsham 2021, Crystal had significantly higher podding biomass at TOS 2 than at TOS 1, whereas other varieties did not differ significantly between TOS 1 and TOS 2 (Figure 5A). For Woomelang 2021, Jade-AU had higher podding biomass at TOS 2 than at TOS 1, whereas other varieties were not significantly different between TOS 1 and TOS 2 (Figure 5B).

3.5 | Harvest Biomass

Harvest biomass was primarily driven by site (W = 334.08, $p < 0.001$) and year (W = 57.67, $p < 0.001$). The highest mean harvest biomass was recorded at Rutherglen 2020 (4131 kg/ha) and Hamilton 2021 (3572 kg/ha) (Table 4). Additionally, harvest biomass exhibited complex environmental sensitivity, evidenced by a significant site × year × variety interaction (W = 25.35, $p < 0.01$) and a site × year × TOS interaction (W = 7.84, $p < 0.05$) (Table 4). For example, Putland performed exceptionally well at Rutherglen 2020 (5240 kg/ha) but significantly lower at Horsham 2021 (766 kg/ha) (Table 5 and Figure S1B). Furthermore, TOS 2 at Rutherglen 2021 had produced significantly higher biomass compared to TOS 1 (TOS 2 = 3950 kg/ha vs. TOS 1 = 1784 kg/ha) (Figure S2B).

Additionally, in the individual environment analysis, TOS × variety interaction was observed at Horsham 2020, Horsham 2021, Rutherglen 2020 and Woomelang 2020 ($p < 0.05$; Figure 6 and Table S5). In contrast, no significant TOS × variety interaction was observed in the remaining environments. At Horsham 2020 and Rutherglen 2020, Jade-AU (and Putland at Horsham 2020) produced significantly higher biomass in TOS 2. Conversely, at

TABLE 4 | Significance of the main effects and their interactions tested by Wald statistic (W) values in the multi-environment analysis (MET) using REML for the six traits of five mungbean varieties evaluated at five sites (Hamilton, Horsham, Ouyen, Rutherglen and Woomelang) over 2 years (2020 and 2021 summers) and two times of sowing (TOS).

Source	df	Podding biomass (kg/ha)[a]	Harvest biomass (kg/ha)	Harvest index (HI)	Grain weight (mg)	Grain number (grains/m^2)	Grain yield (kg/ha)
Variety	4	24.24***	42.52***	48.00***	2612.00***	34.73***	13.73**
Site	4	274.47***	334.08***	64.20***	127.04***	499.60***	400.40***
Year	1	26.71***	57.67***	3.30 ns	54.39***	19.50***	31.91***
TOS	1	1.73 ns	5.33*	0.28 ns	7.46**	0.54 ns	0.15 ns
Site × variety	14	11.91 ns	82.15***	50.16***	28.04*	78.85***	58.90***
Year × variety	4	11.95*	9.45 ns	30.89***	25.96***	14.81**	11.70*
TOS × variety	4	5.44 ns	13.45**	26.26***	5.72 ns	8.91 ns	8.69 ns
Site × year	3	19.61***	80.01***	50.43***	39.33***	80.61***	77.82***
Site × TOS	4	10.21*	32.09***	9.77 ns	5.07 ns	17.71**	17.50**
Year × TOS	1	4.84*	0.25 ns	0.23 ns	1.90 ns	0.08 ns	0.05 ns
Site × year × TOS	3	3.02 ns	7.84*	24.77***	7.93*	25.52***	14.01**
Site × year × variety	9	3.64 ns	25.35**	15.97 ns	20.63*	19.25*	23.97**

Note: Values are Wald statistics (W).
Abbreviation: ns = non-significant.
[a]Excludes Rutherglen 2020 and 2021.
***$p < 0.001$.
**$p < 0.01$.
*$p < 0.05$.

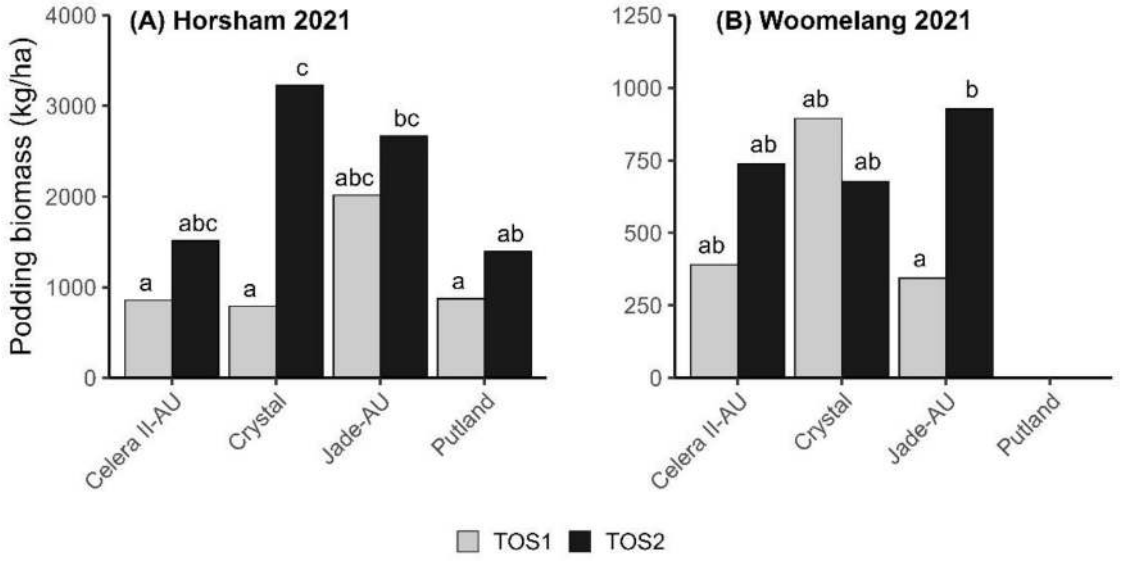


FIGURE 5 | Podding biomass (kg/ha) of mungbean varieties at (A) Horsham 2021 and (B) Woomelang 2021, where time of sowing (TOS) is compared. Bars followed by different letters differ significantly according to Tukey's HSD test at $p < 0.05$.

Horsham 2021 and Woomelang 2020, Jade-AU produced the highest biomass in TOS 1. The variety effect was significant in Ouyen 2021 ($p = 0.043$) and Rutherglen 2021 ($p = 0.002$), whereas there was no significant varietal effect on biomass at Hamilton 2021, Ouyen 2020 and Woomelang 2021 (Tables 5 and S5). Crystal had significantly higher biomass at Ouyen 2021, whereas Putland recorded the highest biomass at Rutherglen 2021.

3.6 | HI

The efficiency of biomass partitioning was governed by a highly significant site × year × TOS interaction (W = 24.77, $p < 0.001$), whereas variety had significant year × variety (W = 30.89, $p < 0.001$), TOS × variety (W = 26.26, $p < 0.001$) and site × variety (W = 50.16, $p < 0.001$) interactions (Table 4). The MET analysis

TABLE 5 | Average podding biomass (kg/ha), harvest biomass (kg/ha), harvest index (HI), grain weight (mg), grain number (grains/m^2) and yield (kg/ha) of mungbean varieties across two times of sowing at Hamilton, Horsham, Ouyen, Rutherglen and Woomelang during the 2020 and 2021 summers. Empty cells indicate that the variety was not tested.

		Hamilton	Horsham		Ouyen		Rutherglen		Woomelang	
Trait	**Variety**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**	**2020**	**2021**
Podding biomass (kg/ha)	Jade-AU	2849	3213 b	2342 b	1120 c	882	NA	NA	2280	635
	Celera II-AU	2425	2699 ab	1184 a	648 ab	857	NA	NA	1669	564
	Golden Dragon		1984 a		475 a	947	NA	NA	1334	833
	Putland	2447	3370 b	1135 a	1130 c		NA	NA	2337	
	Crystal		3567 b	2010 ab	1037 bc	748	NA	NA	1954	787
	Mean	2574	2967	1668	1095	859	NA	NA	1915	662
	p-value	ns	0.002	0.007	0.014	ns	NA	NA	ns	ns
Harvest biomass (kg/ha)	Jade-AU	3728	2952 b	1221	1244	2100 ab	5300 b	3359 b	2893 b	494
	Celera II-AU	3080	1948 a	1034	1018	1745 ab	3947 b	2487 ab	2272 ab	290
	Golden Dragon		1795 a		972	1201 a	1355 a	1074 a	1663 a	394
	Putland	3907	2813 b	766	737		5240 b	4010 b	2149 ab	
	Crystal		2671 b	901	943	2245 b	4816 b	3407 b	2428 ab	316
	Mean	3572	2436	981	983	1823	4131	2867	2281	383
	p-value	ns	<0.001	ns	ns	0.043	<0.001	0.002	<0.001	ns
Harvest index (HI)	Jade-AU	35	43	42 b	33	40	25 a	42 b	42	21
	Celera II-AU	40	45	42 ab	40	30	38 b	42 b	44	18
	Golden Dragon		45		30	29	41 b	43 b	41	25
	Putland	38	44	24 a	33		34 ab	35 a	37	
	Crystal		41	31 ab	44	37	33 b	42 b	35	26
	Mean	38	44	35	36	34	34	41	40	22
	p-value	ns	ns	0.029	ns	ns	0.001	<0.001	ns	ns
Grain weight (mg)	Jade-AU	70.2 c	83.4 d	77.2 bc	74.1 c	82.1 c	73.4 d	62.8 d	76.5 c	68.4 b
	Celera II-AU	36.7 a	42.5 a	40.1 a	40.2 a	41.5 a	38.5 a	32.2 a	38.9 a	37.1 a
	Golden Dragon		55.3 b		49.4 b	53.2 b	46.8 b	45.9 b	53.4 b	46.1 a
	Putland	61.3 b	73.7 c	67.9 b	75.7 c		66.6 c	52.0 c		
	Crystal		83.9 d	85.8 c	76.8 c	77.0 c	74.9 d	61.5 d	79.4 c	66.7 b
	Mean	56.1	67.7	67.7	63.2	63.4	60.1	50.9	62.1	54.6
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

(Continues)

TABLE 5 | (Continued)

Trait	Variety	Hamilton	Horsham		Ouyen		Rutherglen		Woomelang	
		2021	2020	2021	2020	2021	2020	2021	2020	2021
Grain number (grains/m^2)	Jade-AU	1867	1502 ab	683 ab	568 a	1030	1682 ab	2229 b	1597 a	125
	Celera II-AU	2880	2133 b	1036 b	1085 b	1278	3932 c	3826 c	2549 b	145
	Golden Dragon		1459 ab		557 a	683	1124 a	949 a	1260 a	210
	Putland	2383	1147 a	330 a	367 a		2742 bc	2731 bc	1078 a	
	Crystal		1359 a	347 a	550 a	1080	2011 ab	2339 b	1064 a	115
	Mean	2377	1520	599	626	1017	2298	2415	1510	149
	p-value	ns	0.011	0.002	0.001	ns	<0.001	0.001	0.001	ns
Yield (kg/ha)	Jade-AU	1308	1246 c	509 b	420	858 ab	1203 ab	1408 b	1199 b	87
	Celera II-AU	1241	902 ab	421 ab	433	533 ab	1265 ab	1024 ab	986 ab	55
	Golden Dragon		807 a		276	364 a	558 a	454 a	674 a	101
	Putland	1444	1183 bc	191 a	282		1803 b	1391 b	906 ab	
	Crystal		1119 bc	298 ab	425	888 b	1495 b	1450 b	855 ab	79
	Mean	1331	1052	355	368	661	1265	1145	924	81
	p-value	ns	0.001	0.017	ns	0.038	0.002	0.004	0.044	ns

Note: Results are from individual environment (site × year combination) analysis using REML. Mean values with the same letter within each environment do not differ significantly at $p = 0.05$.

suggests that the ability of mungbean varieties to convert biomass into grain is not fixed but is highly dependent on environment (site and year) and TOS (Table 5 and Figures S1C and S2C). The lowest predicted value was observed at Woomelang 2021 (TOS 2) with a mean of 18, which was significantly lower than most of the other environments. HI in Hamilton 2021, Rutherglen 2021, Horsham 2021 and Ouyen 2021 remained statistically consistent between TOS 1 and TOS 2, whereas at other sites, the response was substantially different between TOS 1 and TOS 2 (Figure S2C).

Additionally, through the individual environment analysis, the significant interaction between variety and TOS was recorded at Horsham 2020, Rutherglen 2020, Rutherglen 2021 and Woomelang 2021 ($p < 0.05$, Figure 7 and Table S5). In general, Putland, Jade-AU and Crystal had higher HI at TOS 1 and Golden Dragon at TOS 2 (Figure 7), as TOS 1 had higher HI for Putland at Horsham 2020, Rutherglen 2020 and Rutherglen 2021 and for Jade-AU and Crystal at Rutherglen 2020 and Woomelang 2021. Conversely, Golden Dragon achieved higher HI at TOS 2 at Rutherglen 2021. The variety effect was significant in Horsham 2021 ($p < 0.05$), Rutherglen 2020 and Rutherglen 2021 (Tables 5 and S5). Highest HI was recorded in Golden Dragon (Rutherglen 2020 and Rutherglen 2021) and Jade-AU (Horsham 2021), whereas lowest HI values were recorded for Putland at Horsham 2021 and Rutherglen 2021 and for Jade-AU at Rutherglen 2020. There was no significant varietal effect on HI at other environments, where the mean ranged from 22 to 44 (Table 5).

3.7 | Grain Weight

Grain weight remained the most genetically stable trait, dominated by a massive variety effect (W = 2612.00, $p < 0.001$) (Table 4). Despite significant site × year × variety (W = 20.63, $p < 0.05$) and site × year × TOS (W = 7.93, $p < 0.05$) interactions (Table 4), varietal rankings for grain weight remained largely unchanged (Table 5 and Figure S1D). Across all testing environments, Crystal consistently produced the largest grains (range: 61–86 mg and average: 76 mg) along with Jade-AU (range: 63–83 mg and average: 74 mg), whereas Celera II-AU consistently produced the smallest (range: 32–43 mg and average: 39 mg) (Table 5). The effect of TOS on grain weight was not significant across the environments except at Horsham 2021 ($p = 0.001$, Table S5), where TOS 2 (72.1 mg) had significantly higher grain weight compared to TOS 1 (63.5 mg) (Figure S2D).

3.8 | Grain Number

The effect of TOS and variety was environment dependent for grain number (grains/m^2) due to the significant three-way site × year × TOS interaction (W = 25.52, $p < 0.001$) and site × year × variety interaction (W = 19.25, $p < 0.05$) (Table 4). At Rutherglen in 2021, TOS 2 resulted in a significantly higher grain number (3294 grains/m^2) compared to TOS 1 (1464 grains/m^2) (Figure S2E). However, in other sites, the differences between TOS 1 and TOS 2 were marginal and statistically non-significant

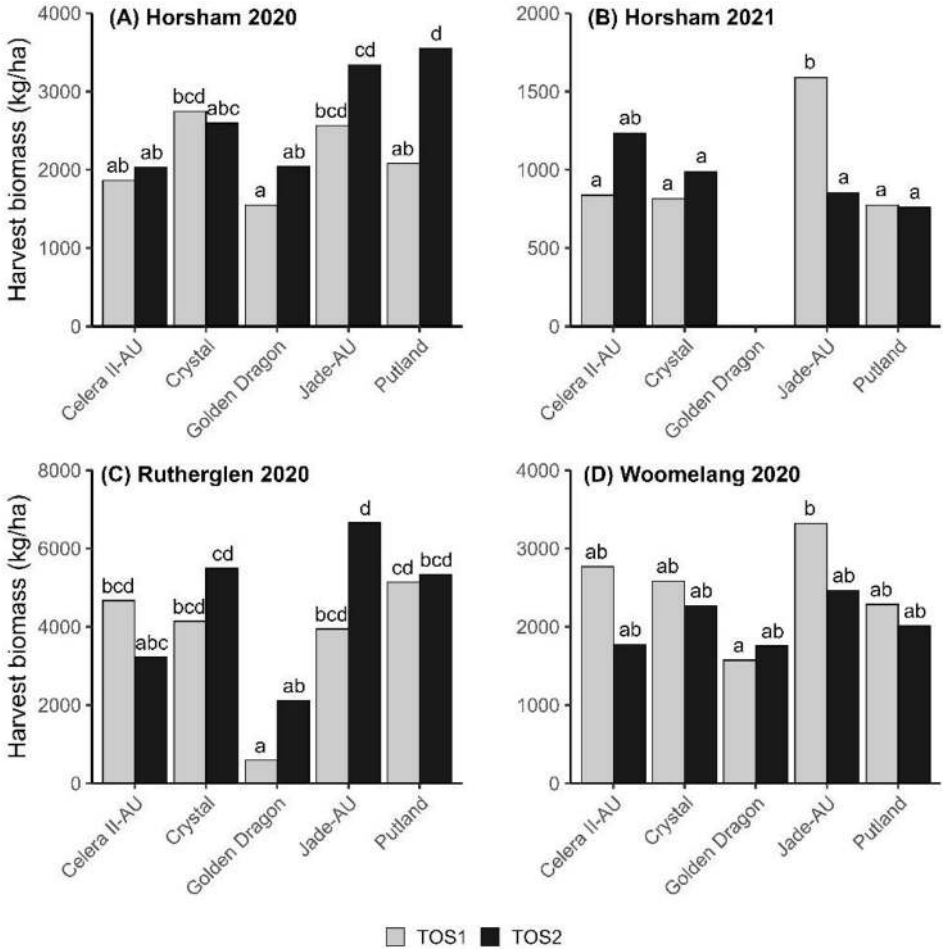


FIGURE 6 | Harvest biomass (kg/ha) of mungbean varieties at (A) Horsham 2020, (B) Horsham 2021, (C) Rutherglen 2020 and (D) Woomelang 2020, where time of sowing (TOS) is compared. Bars followed by different letters differ significantly according to Tukey's HSD test at $p < 0.05$.

(Figure S2E). The site × year × variety interaction resulted in varieties Putland and Golden Dragon showing contrasting responses in grain number across the environments (Figure S1E). Putland demonstrated high grain number potential in favourable environments, achieving the highest grain number at Rutherglen 2020 (3842 grains/m^2), but recorded lowest in less favourable environments like Horsham 2021. In contrast, Golden Dragon displayed greater relative stability, although it never recorded significantly higher grain numbers like Putland. Additionally, in the individual environment analysis, varietal differences were significantly TOS dependent in Rutherglen 2020, Rutherglen 2021 and Horsham 2021 (Figure 8 and Table S5). At Rutherglen 2020, Celera II-AU was significantly higher at TOS 1 as compared with TOS 2 (4640 vs. 3225 grains/m^2, respectively), whereas Golden Dragon recorded higher peaking at TOS 2 (1685 vs. 563 grains/m^2 for TOS 1) (Figure 8A). At Rutherglen 2021, grain number was significantly higher in TOS 2 compared to TOS 1 for all the varieties except for Golden Dragon (Figure 8B). At Horsham, Jade-AU favoured TOS 1 (936 vs. 430 grains/m^2 for TOS 2), whereas Celera II-AU produced a higher grain number at TOS 2 (1277 vs. 796 grains/m^2 for TOS 1) (Figure 8C). The variety differences on grain number were significant at six environments (Horsham 2020, Horsham 2021, Ouyen 2020, Rutherglen 2020, Rutherglen 2021 and Woomelang 2020), with Celera II-AU consistently maintaining the highest grain number and Putland, Golden Dragon or Crystal recording the lowest depending on the site (Tables 5 and S5).

3.9 | Yield

Combined REML analysis of variance of multilocation trials revealed significant site × year × variety (W = 23.97, $p < 0.01$) and site × year × TOS (W = 14.01, $p < 0.01$) interactions (Table 4). Putland achieved the highest yield at Rutherglen 2020, but it was among the worst performers at Horsham 2021 (Table 5 and Figure S1F). Such a high degree of phenotypic plasticity suggests that certain varieties are specifically adapted to favourable environments (e.g., Rutherglen 2020) but lack the stability required for consistent performance in lower yielding environments like Horsham 2021. Under these interactive pressures, Jade-AU emerged as the most resilient variety, consistently ranking in the highest yielding group across both high-yielding and stressful environments. Rutherglen was the highest yielding site in both years (1265 and 1145 kg/ha), whereas the lowest yields occurred at Ouyen 2020 (368 kg/ha) and Woomelang 2021 (81 kg/ha) (Table 5).

At Rutherglen in 2021, TOS 2 resulted in a significantly higher yield (1576 kg/ha) compared to TOS 1 (715 kg/ha) (Figure S2F).

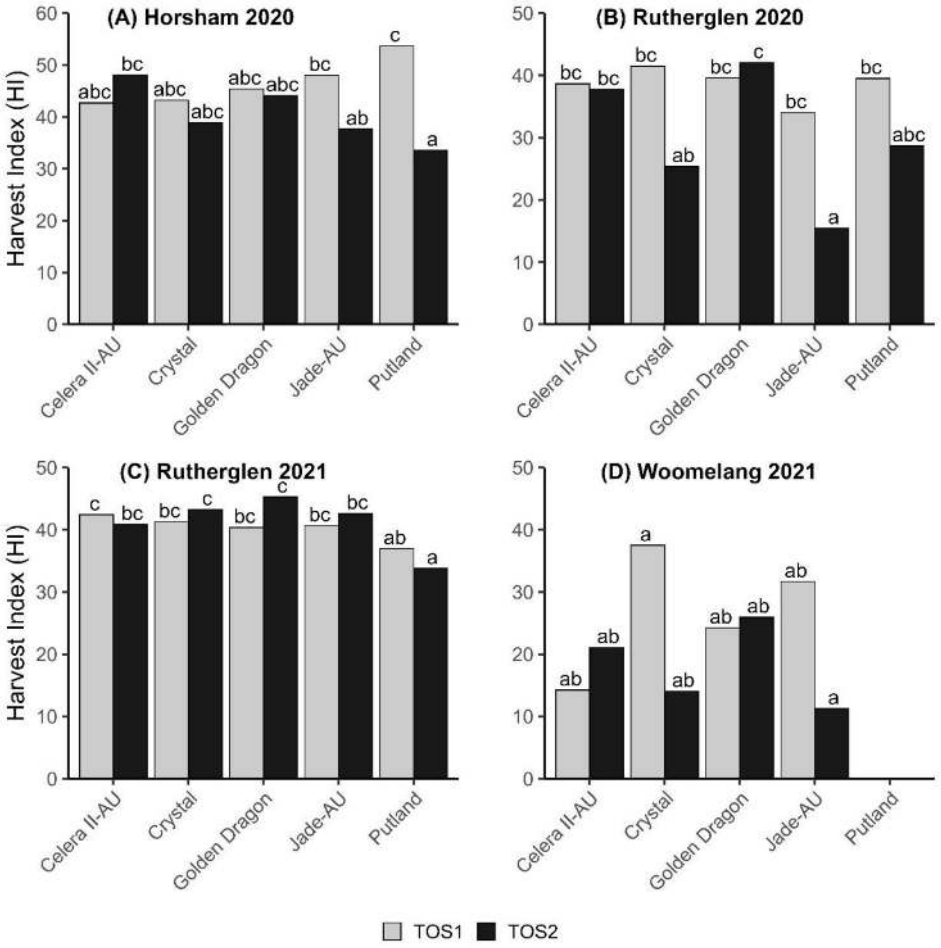


FIGURE 7 | Harvest index (HI) of mungbean varieties at (A) Horsham 2020, (B) Rutherglen 2020, (C) Rutherglen 2021 and (D) Woomelang 2021, where time of sowing (TOS) is compared. Data with the same letter within a treatment are not significantly different at $p < 0.05$.

However, in other sites, the differences between TOS 1 and TOS 2 were marginal and statistically non-significant (Figure S2F).

Individual environment (site × year) analyses showed that there was a significant effect of variety on grain yield in six of the nine environments, with Ouyen 2020, Hamilton 2021 and Woomelang 2021 being the exceptions (Tables 5 and S5). Jade-AU was the highest yielding variety at Horsham 2020, Horsham 2021 and Woomelang 2020. Crystal recorded the highest yield at Ouyen 2021 and Rutherglen 2021. Putland was the highest yielding variety at Rutherglen in 2020. Golden Dragon had the lowest yield at five sites (Horsham 2020, Ouyen 2021, Rutherglen 2020, Rutherglen 2021 and Woomelang 2020) and Putland at Horsham 2021.

3.10 | Grain Quality of Variety Jade-AU

The grain quality of mungbean variety Jade-AU was comparable to that of the source seed produced in subtropical Australia, showing similar grain size (range 67–80 mg) and protein content (range 28%–30% dry weight); however, its brightness (range 36–38 L*) was lower than that of the source seed. The grain size, protein and grain brightness of source seed were 70 mg, 27% and 40 L*, respectively.

3.11 | Relationship Among Yield, Yield Components and Varieties

Across all sites and years, grain yield was significantly correlated with podding biomass ($r = 0.70^{***}$, $n = 57$), harvest biomass ($r = 0.91^{***}$, $n = 80$), HI ($r = 0.27^{*}$, $n = 80$) and grain number ($r = 0.81^{***}$, $n = 80$) but not correlated with grain weight. Grain yield was also significantly correlated with HI ($r = 0.54^{**}$, $n = 40$) and grain weight ($r = 0.31^{**}$, $n = 40$) for TOS 1 but were not correlated for TOS 2. However, grain yield was correlated with podding biomass (TOS 1: $r = 0.75^{***}$, $n = 27$; TOS 2: $r = 0.71^{***}$, $n = 30$), harvest biomass (TOS 1: $r = 0.96^{***}$, $n = 40$; TOS 2: $r = 0.88^{***}$, $n = 40$) and grain number (TOS 1: $r = 0.79^{***}$, $n = 40$; TOS 2: $r = 0.84^{***}$, $n = 40$) at both TOS 1 and TOS 2. Additionally, the harvest plant density was positively correlated with grain yield ($r = 0.27^{*}$, $n = 60$, $R^2 = 0.08$) and podding biomass ($r = 0.47^{***}$, $n = 57$, $R^2 = 0.23$) across all sites and years, though the relationship was weaker for grain yield. However, harvest plant density was correlated with grain yield ($r = 0.44^{*}$, $n = 30$), HI ($r = 0.54^{***}$, $n = 30$) and podding biomass ($r = 0.73^{***}$, $n = 27$) at TOS 1 but not at TOS 2.

PCA of yield components captured 79.3% of the total variance in the first two dimensions (Figure 9). PC1 (58.2%) was defined by yield, harvest biomass and grain number with the

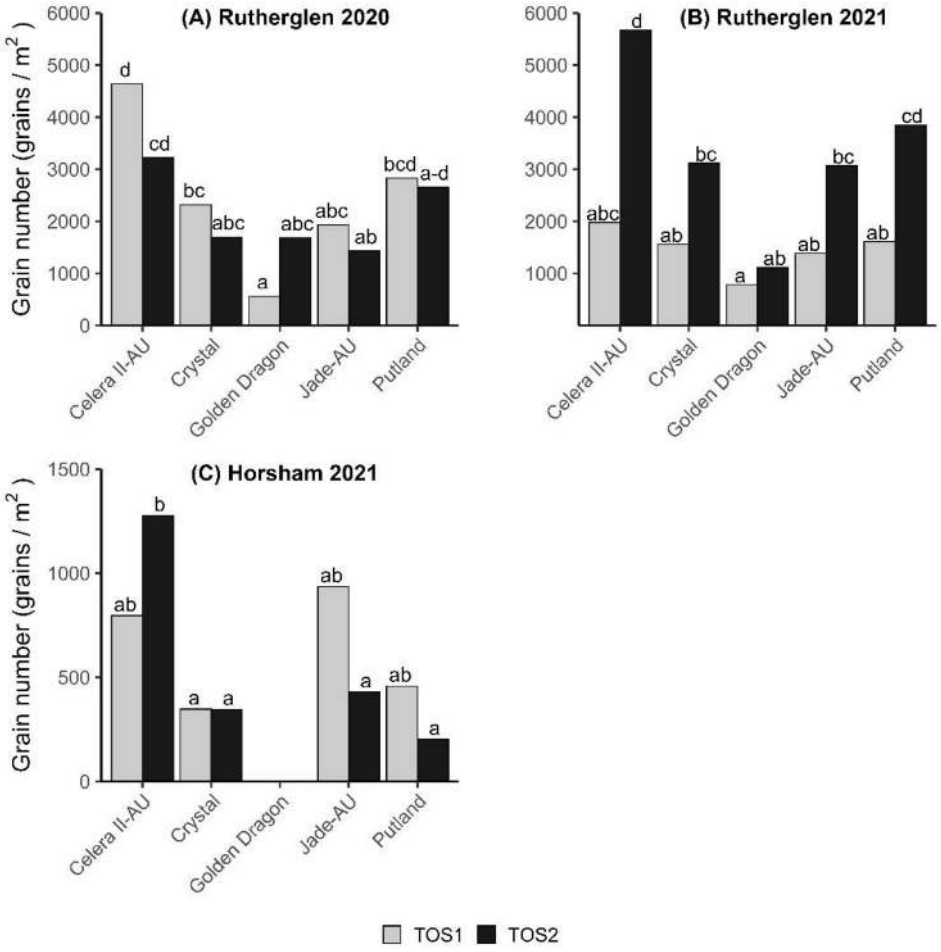


FIGURE 8 | Grain number (grains/m^2) of mungbean varieties across two times of sowing (TOS) at (A) Rutherglen 2020, (B) Rutherglen 2021 and (C) Horsham 2021, where TOS is compared. Bars followed by different letters differ significantly according to Tukey's HSD test at $p < 0.05$.

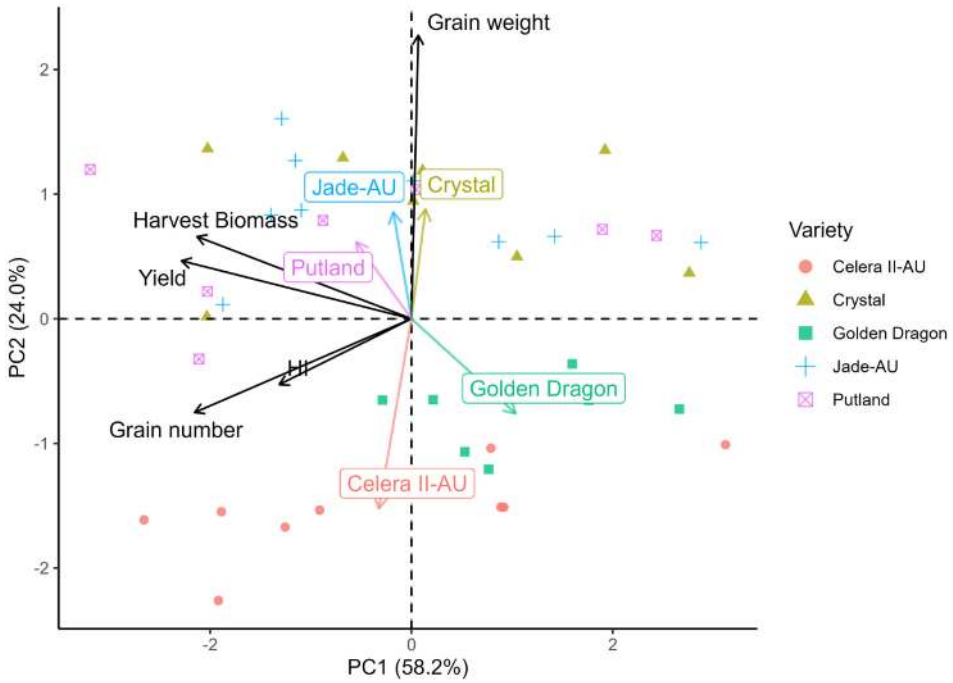


FIGURE 9 | Biplot showing the relationship among yield, yield components (harvest biomass, grain number, grain weight and HI) and five mungbean varieties (Celera II-AU, Crystal, Golden Dragon, Jade-AU and Putland). Principal component analysis (PCA) was conducted using the best linear unbiased estimates (BLUEs) derived from multi-environment trail (MET) analysis.

contribution of 32.4%, 28.8% and 28.2%, respectively (Table S6). Additionally, PC1 clearly identified Jade-AU and Putland as the high performing varieties with their higher biomass accumulation and grain number. Conversely, PC2 (24.0%) was defined by grain weight (77.7% contribution), with Crystal being highly correlated with grain weight. In the biplot (Figure 9), the grain weight and yield vectors are situated nearly at a 90° angle (orthogonal), confirming that grain weight had little influence on yield variation. This multivariate alignment is consistent with the univariate results, which also showed no significant correlation between yield and grain weight across the environment. Although Celera II-AU and Golden Dragon clustered towards lower yield and grain weight relative to other varieties in the tested environments, the overall results indicate that mungbean productivity in these environments is driven by the function of biomass and grain number rather than grain weight or partitioning efficiency (HI).

3.12 | AMMI Analysis of Yield for Environmental Correlations

The average yield of mungbean varieties ranged from 55 to 1803 kg/ha (Table 5). An AMMI analysis revealed highly significant ($p < 0.001$) main effects for genotype, environment and the G × E interaction (Table S7). The G × E interaction was decomposed into interaction principal component axes 1 (IPCA 1) and interaction principal component axes 2 (IPCA 2). IPCA 1 and IPCA 2 explained 68.12% and 19.53% of the total variation in the G × E interaction, respectively (Figure 10). These two principal components explained 87.65% of the G × E interaction. The angle between Rutherglen 2020 and Rutherglen 2021 is less than 90°, reflecting the positive correlation between the environments.

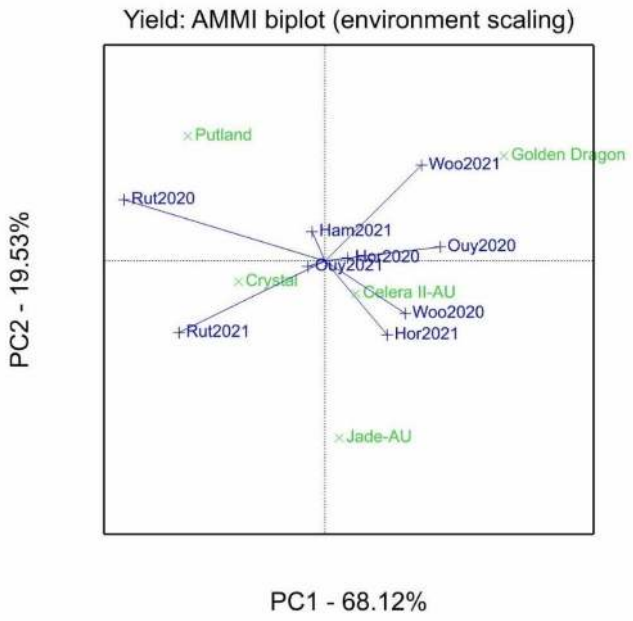


FIGURE 10 | AAMI biplot showing relationship among test environments and genotypes for grain yield. Environments: Sites are identified as Ham (Hamilton), Hor (Horsham), Ouy (Ouyen), Rut (Rutherglen) and Woo (Woomelang), followed by the trial year (e.g., Ham2021 = Hamilton 2021).

Rutherglen 2020 and Rutherglen 2021 have more than 90° with other sites, except for Ouyen 2021 and Hamilton 2021, indicating a negative correlation between them. Putland, Jade-AU and Celera II-AU exhibited the highest average yield across all the environments (Figure 11), whereas Crystal demonstrated broader adaptability by its proximity to the origin (Figure 10). Jade-AU and Putland were highly influenced by environmental interaction, as represented by their relative distance from the origin compared to Celera II-AU.

The mega-environment function analysis divided the nine environments into three distinct mega-environments (Figure 12). Hamilton 2021 and Rutherglen 2020 formed a distinct mega-environment (M1); the second was Horsham 2021 (M2), and the rest of the environments formed the final mega-environment (M3). Putland was the best performing variety in M1; Celera II-AU was best suited in M2, and Jade-AU and Crystal performed best in M3. M2 is characterised by Horsham 2021, and Golden Dragon was not tested in Horsham 2021, making Golden Dragon unsuitable for any specific mega-environment.

4 | Discussion

4.1 | Influence of Sowing Time, Establishment and Phenology on Yield and Yield Components

The effect of TOS was tested by sowing mungbean varieties from mid-October to mid-December across low, medium and high rainfall environments of Victoria. Sowing in late spring and early summer provided insights into the degree of adaptation of the crop to new environments in response to abiotic stresses (Rahman et al. 2005; Richards et al. 2022). It is essential to study the response of sowing times to mitigate risks associated with environmental stresses such as cold at sowing, as well as heat and drought, which have significantly adverse effects on growth, particularly during critical developmental phases like flowering and podding (Chauhan and Williams 2018; Bangar et al. 2019; Wenham et al. 2020; Bhardwaj et al. 2023). Final yields were influenced by soil temperature, flower initiation and water availability on establishment, biomass and grain number.

First, soil temperature at sowing was strongly related to emergence time and, subsequently, final establishment. Lower soil temperatures resulted in longer emergence times and lower plant densities similar to results under controlled environment (Silwal et al. 2026). Mungbean was found to germinate favourably between 30°C and 40°C and exhibited the fastest rate at 40°C under controlled conditions without water limitation (Fyfield and Gregory 1989). A similar result was also reported by Amin et al. (2023), with maximum germination rate between 25°C and 35°C and the maximum germination percentage at 30°C. However, Chauhan and Williams (2018) reported that the required soil temperature for effective germination was more than 15°C. In our experiments, soil temperatures to a depth of 10 cm exceeded 15°C by the end of September for Ouyen, whereas in Horsham, the soil temperature reached 15°C by the end of October, and in Hamilton, it reached 15°C by the end of November. Thus, northern Victorian sites (Ouyen and Woomelang) had favourable soil temperatures in early spring (October), whereas southern sites (Hamilton) had favourable

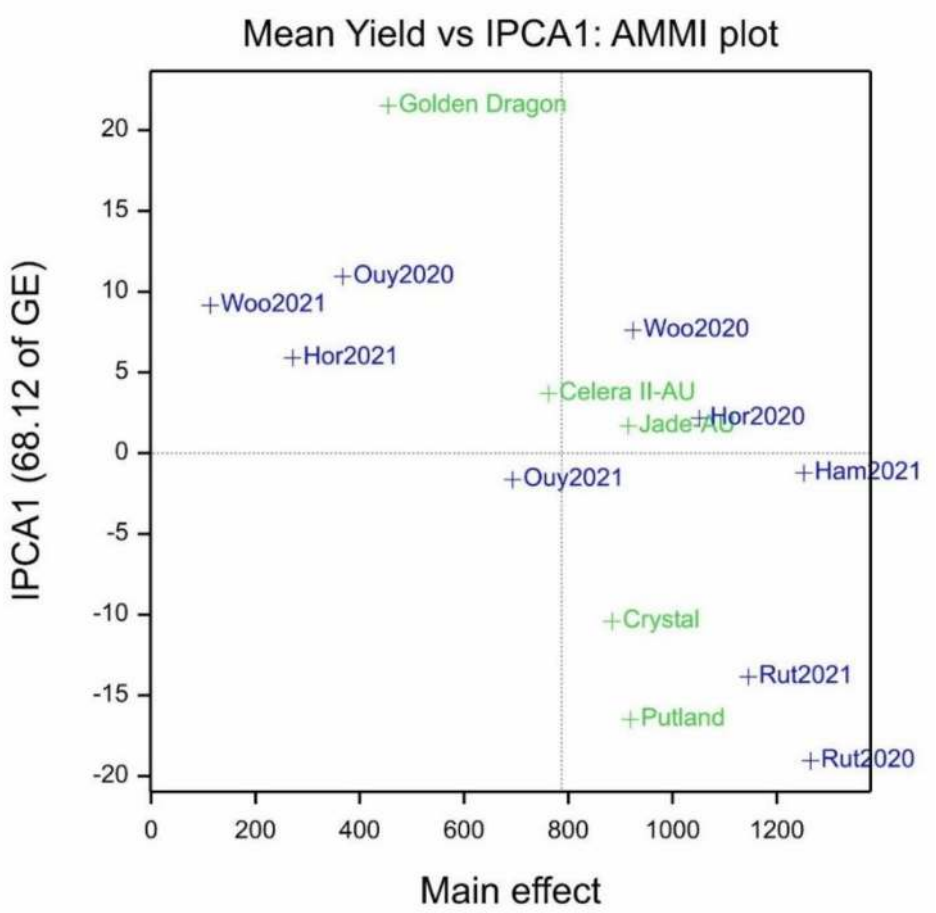


FIGURE 11 | AMMI biplot for additive effects versus IPCA 1. Environments: Sites are identified as Ham (Hamilton), Hor (Horsham), Ouy (Ouyen), Rut (Rutherglen) and Woo (Woomelang), followed by the trial year (e.g., Ham2021 = Hamilton 2021).

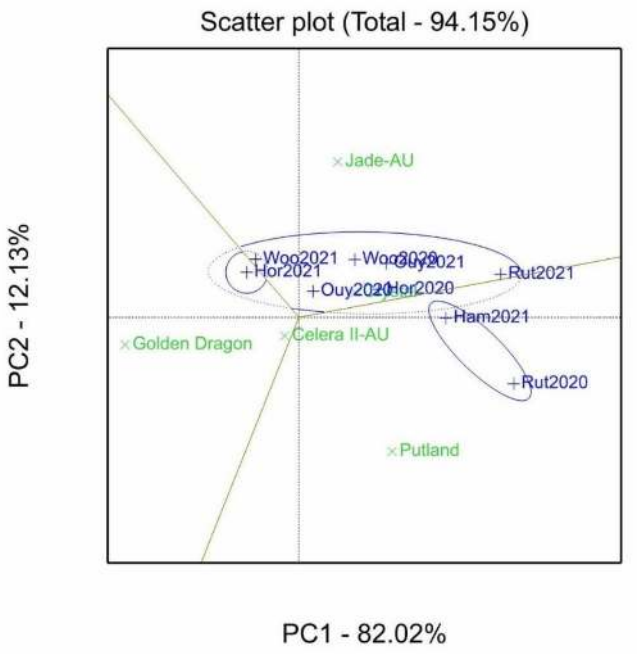


FIGURE 12 | GGE biplot for grain yield showing which genotype performed best in which environment. Environments: Sites are identified as Ham (Hamilton), Hor (Horsham), Ouy (Ouyen), Rut (Rutherglen) and Woo (Woomelang), followed by the trial year (e.g., Ham2021 = Hamilton 2021).

temperatures during early summer (December). Therefore, the optimal time for seed sowing under Victorian conditions is from late spring to early summer. Understanding the variation in the response of mungbean varieties to soil temperature during sowing times (October–December) is important for successful early establishment. However, although harvest plant density was significantly correlated with grain yield ($r = 0.27^*$), the low R^2 value (0.08) suggests that plant density was a minor driver of yield variability across the tested environments. This indicates that approximately 92% of the variance in yield was likely attributable to other factors, such as moisture stress during flowering or G×E interactions, rather than initial establishment success alone.

Second, the effect of the TOS was not significant on yield at any of the sites, except at Rutherglen in 2021. This could be due to the phenological response of varieties to photoperiod requirement for floral initiation. As most varieties across the trials flowered in February, crops sown at both times were subject to similar weather conditions during podding, grain filling and maturity at each site.

TOS of mungbean varieties influenced the DTFF (Figure 4) as reported by Ellis et al. (1994) and Imrie and Lawn (1990). However, the varieties tested in this study did not exhibit variability in DTFF within each TOS at each environment. Understanding how mungbean varieties respond to sowing

time and temperature is crucial for developing strategies for varietal adaptation to new growing environments. Mungbean varieties were cultivated in various locations and sowing dates to assess their phenological response to differing temperatures and day lengths. Flowering initiation is determined by temperature in photoperiod-insensitive plants, whereas in photoperiod-sensitive plants, flowering initiation is influenced by both temperature and day length (Horie 1994). Even though the previous research on mungbean reported photoperiod sensitivity of older Australian varieties (Imrie and Lawn 1990), current varieties tested in this experiment were not characterised for photoperiod sensitivity prior to this research (Geetika, Collins, et al. 2022). Although the varieties examined in this study displayed minimal intravarietal variation in DTFF within a specific TOS, they collectively displayed photoperiod sensitivity. Specifically, longer day lengths delayed flowering in earlier-sown mungbean, resulting in a higher number of GDDs required for flowering (Poehlman 1991). This sensitivity effectively synchronised flowering across different sowing dates to a specific window in February; such 'phenological synchronisation' can serve as a critical adaptive mechanism in southern Australian cropping systems as noted by Gaynor et al. (2012) for soybean systems in the Riverina region in Australia.

Third, this photoperiodic synchronisation had a direct impact on yield components. By regulating the duration of the vegetative phase, it influenced biomass accumulation, which we found to be the strongest predictor of grain yield ($r = 0.91^{***}$). The high correlation between yield and grain number ($r = 0.81^{***}$) suggests that mungbean yield in these environments is 'sink-limited', where the 'source' (biomass) established prior to grain filling determines the number of successfully developed pods (Wenham and Collins 2024). Gaynor et al. (2012) also had a similar relationship for soybean in southern New South Wales, Australia, with a strong linear relation between yield and biomass when the crop matured before frost. The dominant correlation between yield and biomass indicates that under the conditions of this study, biomass production was the primary constraint on seed yield, suggesting that the 'source' capacity was not yet saturated. Although HI showed a significant correlation ($r = 0.54^{**}$), its secondary role implies that yield stability in these marginal temperate regions is best achieved by maximising total dry matter accumulation rather than solely focusing on partitioning efficiency. The phenological plasticity due to photosensitivity may enhance the adaptability of the mungbean varieties in southern Australian cropping systems by offering a broader sowing window while reducing the risk of cold stress at the reproductive stage later in the season (Farrell et al. 2006), while allowing the crop enough time to build the biomass necessary to support a higher grain number. Therefore, breeding efforts in this region should prioritise (i) varieties that maintain this photoperiodic sensitivity to ensure flowering occurs within the safest climatic window regardless of sowing date; (ii) varieties with a higher rate of dry matter accumulation prior to photoperiod-triggered flowering and grain filling for the increased yield; and (iii) varieties selected for a stable HI to ensure the effective conversion of biomass (source) to grain number (sink).

Water availability during the flowering and pod filling stages of mungbean had a significant influence on grain number (Wenham et al. 2020; Silwal et al. 2025). Water stress during this stage can reduce pod set by 10%–35%, resulting in a 75% yield reduction if stress occurs during pod development (Wenham et al. 2020). Grain number is largely governed by successful pod formation and pollen viability (Patriyawaty et al. 2018). The higher rainfall in Ouyen in 2021 (119 mm) during flowering and pod filling may have had a positive impact on grain filling and grain set compared to Ouyen in 2020, when 52 mm of rainfall was received, and supplementary irrigation was applied during the vegetative and sowing periods. For the lowest yielding site, Woomelang in 2021, the crop received only 4 mm of water from DTFF to maturity (i.e., from 1 January 2022 to 1 March 2022), as it did not receive any supplementary irrigation during the vegetative and reproductive stages, thus limiting yield potential. In contrast, Rutherglen in 2021 recorded the highest grain number and yield across sites, corresponding to the higher rainfall (374 mm) received during the growing period. However, assuming that 5 days of rainfall of > 30 mm between October and December for sowing and > 150 mm of rainfall within 90 days of sowing is necessary for a successful crop, an analysis of the likelihood of a successful crop without supplementary irrigation would only be feasible at Rutherglen in 65% of years from 1919 to 2018, 55% of years in Hamilton, 33% at Horsham, 29% at Ouyen and 20% at Woomelang (data not presented). Therefore, for sites like Horsham, Ouyen and Woomelang, the use of stored water plus irrigation needs to be considered due to the reduced chances of follow-up rainfall (Silwal et al. 2025).

In addition to water availability at critical growth stages, mungbean is sensitive to high temperatures, with temperatures exceeding 35°C (Bhardwaj et al. 2023) causing mungbean to lose flowers and pods (Geetika, Hammer, et al. 2022). Similar effects were reported in cowpea, where high temperatures affecting the grain set resulted in reduced yield (Porch and Hall 2013). The flowering and grain filling stages following early sowing (TOS 1) are likely to experience high peak summer temperatures. The difference in yield between the sites is likely in part to be attributed to the exposure of mungbean to high temperatures during flowering and podding. These high temperatures may have caused significant sterility and reduced pod set across the sites, leading to yield losses. Woomelang and Ouyen experienced at least 8 days with temperatures above 36°C during flower initiation to 30 days after flowering across the trials. In contrast, at Horsham, the number of days above 36°C during the same period was five in 2020 and six in 2021. At Rutherglen, temperatures never exceeded 36°C during the flowering and pod filling stages across the trials. The mungbean crop faces a higher risk of exposure to elevated temperatures at Ouyen and Woomelang during pod filling compared to Rutherglen and Hamilton. Furthermore, the potential expansion of mungbean cultivation into temperate regions due to global warming is a double-edged sword, presenting both opportunities and challenges. Rising average temperatures may extend the frost-free growing season and improve soil conditions for spring establishment. However, the advantage of a wider thermal window is frequently offset by an increased occurrence of heat spikes above 35°C, which induce flower abortion and reduce grain number (Geetika, Hammer, et al. 2022). The photoperiod sensitivity observed in varieties such as Jade-AU and Crystal, which delayed flowering in earlier sowings, indicates that this natural buffering mechanism could be utilised to synchronise flowering

with cooler periods, thereby lowering the risks associated with a warming climate.

Lower temperature of 12°C during flowering and pod filling for 5 days could decrease mungbean yield by up to 50% (Xiang et al. 2023). The mungbean crops were exposed to low temperatures (< 12°C) during flowering (5 days in January and 9 days in February) at Ouyen 2020. This resulted in lower grain number in Ouyen 2020 compared to Ouyen 2021, which experienced only 9 days of low temperature below 12°C in February and subsequent loss of yield. The lower temperatures significantly impact the grain number by negatively affecting pollen tube development on reproductive activities, leading to lower fertilisation, resulting in low yield (Gao et al. 2014). Additionally, lower temperature reduces sucrose content, resulting in lower photoassimilates to the reproductive organs, leading to floral drop (Xiang et al. 2023). The likelihood analyses of the percentages of occurrences of lower temperatures of below 12°C for up to 5 days as in Xiang et al. (2023) during the flowering time of February in Ouyen, Woomelang, Horsham, Hamilton and Rutherglen are 13%, 45%, 67%, 73% and 63% of years, respectively, over the past 30 years, illustrating the impact of low temperatures on grain number and yield across the sites in Victoria. Additionally, the risk of yield penalty associated with different sowing dates due to soil water availability needs to be accounted for and studied. Meanwhile, cold temperatures in the later stages of the crop need to be considered when determining the optimal sowing time. Cold temperatures following flower initiation can delay crop maturity, as temperature plays a critical role in grain filling and maturity, regardless of photoperiod. Rahman et al. (2005) reported that, in their TOS study of soybean varieties in the temperate environment of Canterbury, New Zealand, earlier sowing resulted in a longer duration to flowering compared to sowing closer to the solstice. In temperate regions such as Victoria, the use of earlier maturing varieties that reach physiological maturity by early April can effectively reduce the risk associated with the first killing frost. Further studies on the phenological and physiological responses of the mungbean varieties to the timing of sowing may reveal the mechanisms underlying flowering and the interaction between temperature and photoperiod for the temperate region of Victoria.

4.2 | The G × E Interaction

A significant G × E interaction was observed in the current study as the genotypes behaved differently across environments (Figure 10). The varieties Crystal and Celera II-AU are close to the principal component origin, indicating their stability across the test environments. In contrast, Putland, Golden Dragon and Jade-AU were distant from the origin, suggesting the suitability of each variety to its distinct environment and their sensitivity to environmental variations (Samonte et al. 2005). Putland and Crystal performed best at the Rutherglen and Hamilton sites, yielding higher as they experienced less heat and water stress. In contrast, Jade-AU grew well in north-west Victorian sites (Ouyen, Woomelang and Horsham), which are characterised by drier and hotter conditions. Golden Dragon consistently produced a low yield across all environments and was located in a sector that did not encompass any specific mega-environment (Figure 12) and is thus not suitable for Victoria's temperate environments.

Environment plays a critical role in growing mungbean as an opportunistic crop. In our study, the trials in the low to medium rainfall zones of northwestern Victoria (Ouyen, Woomelang and Horsham) were clustered together, indicating that the tested genotypes performed similarly across these trial sites. The trials from Ouyen, Woomelang and Horsham showed a higher positive correlation, except for Ouyen 2021, which might be attributed to similar environmental conditions such as lower rainfall and higher mean temperatures. However, the lack of correlation of Ouyen 2021 with these trials could be due to a significant rainfall event during the reproductive period. The trials with higher in-season rainfall, such as Hamilton 2021, Rutherglen 2020 and Rutherglen 2021, exhibited a positive correlation as these sites had limited water and heat stress. The differences between the trials arise from variations in multiple factors, including soil types, rainfall, supplementary irrigation and temperature. This study highlights the need to consider multiyear variation within a site when interpreting the findings.

5 | Conclusions

The results of these trials indicate that mungbean is feasible as an opportunistic summer crop in northeastern Victoria (Rutherglen) during December. Delaying sowing avoids cooler soil temperatures, thereby improving establishment assuming there is adequate soil water in the seed bed. This environment also mitigates the risks associated with drought and elevated temperatures during flowering and pod filling, particularly in comparison to situations in northwestern Victoria. The current study identifies the optimal sowing period for Ouyen and Woomelang as October to December, for Horsham as November to December, for Rutherglen as November and for Hamilton as December, for all tested varieties, contingent upon sufficient rainfall to initiate a soil water break. However, it is crucial to note that the likelihood of receiving adequate rainfall at Ouyen, Woomelang and Horsham to achieve this break is comparatively low, with subsequent rainfall also proving insufficient to support growth. To achieve the highest possible crop yield, it is vital to prevent drought and heat stress during the critical stages of flowering, podding and grain filling in northeastern Victoria and southwestern Victoria by sowing in December. However, maturity at Hamilton could be delayed due to low temperatures during the grain filling period. The results indicate that the rainfed environments with the drier sites of low and medium rainfall zones of Victoria are not suitable to support mungbean cultivation, meaning it is not a viable option within the cropping system. Furthermore, this study underscores the importance of conducting additional research on current and new cultivars to investigate their physiological and phenological adaptability in the target production environments as the current varieties were found to be photoperiod sensitive. The environmental characterisation of this study aids in determining the production domains of new cultivars and facilitates a more precise understanding of crop–environment interactions. This approach informs breeding for adaptability and provides a practical guide for farmers

in selecting suitable varieties for their specific target environment. Furthermore, the data from this study are essential inputs for biophysical models when integrated with long-term regional climate data. Including these parameters in the modelling enhances the ability to accurately assess the risks that unpredictable weather events present to mungbean establishment and yield stability.

Author Contributions

James G. Nuttall: conceptualization, methodology, writing – review and editing, supervision, resources, project administration, funding acquisition, validation. **Audrey J. Delahunty:** conceptualization, methodology, writing – review and editing, supervision. **Ashley J. Wallace:** methodology, data curation, writing – review and editing. **Sachesh Silwal:** methodology, software, data curation, investigation, validation, formal analysis, visualization, writing – original draft, writing – review and editing. **Sally Norton:** writing – review and editing, supervision. **Alexis Pang:** supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data generated or analysed during this study are presented in this article. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Median biomass sampling and harvest dates for mungbean varieties. **Table S2:**. Model selection for random effect structure based on Restricted Maximum Likelihood (REML). **Table S3:** Model selection for fixed effect structure for yield components based on Restricted Maximum Likelihood (REML). **Table S4:** Flowering dates, GDD and photoperiod by site and year. **Table S5:**. Wald statistics for biomass, HI and yield across sites and TOS. **Figure S1:**. Impact of environment and variety on crop growth and yield components. **Figure S2:** Impact of environment and time of sowing (TOS) on crop growth and yield components. **Table S6:** Principal component analysis of agronomic traits of mungbean varieties at by site and year. **Table S7:** Anova table for AMMI model.