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Evaluating Mungbean (*Vigna radiata*) as an Alternative Specialty Crop for Virginia Tobacco Farmers

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ABSTRACT

Mungbean [*Vigna radiata* (L.) R. Wilczek] is an important grain legume crop in Asia. Mungbean is consumed in the United States by a niche market in Asian cuisines, primarily as bean sprouts. Currently, over two-thirds of mungbeans consumed in the United States are imported, with nearly all domestic production concentrated in Oklahoma. This research explores the potential for Virginia tobacco farmers to grow mungbean as an alternative specialty crop amid declining tobacco demand. Two commercial cultivars, Berken and OK 2000, were planted in a split-plot design across three locations in 2021 and 2022. Seeds were sown at early and late planting dates in June and July on farmers' fields and the research station of Virginia Tech in Southside, VA. Yield and agronomic traits were analyzed using one-way ANOVA for individual locations and years. Because of variable rainfall patterns and differing management practices, no consistent effects of genotype or planting date were observed on yield, plant height, pods per plant, seeds per pod, or seed size. Yields ranged from 0.19 to 1.18 mt ha^{-1}, averaging 0.84 mt ha^{-1} in 2021 and 0.38 mt ha^{-1} in 2022. The highest recorded yield exceeded the global average, and the 2-year mean surpassed India's national average, the world's largest mungbean producer. Our results highlight mungbean's potential in Virginia, though further investment in production systems and research is necessary to optimize its viability as a specialty crop.

1 | Introduction

Mungbean [*Vigna radiata* (L.) R. Wilczek] is a warm-season pulse crop in the *Fabaceae* family, native to India and widely consumed across Asia, particularly in China and Myanmar (Nair et al. 2019). Mungbean's most notable production characteristics are its short growth cycle, maturing in 60–90 days, depending on the variety, and its notable drought tolerance. Compared to corn, mungbean requires approximately 60% less water than corn to produce comparable yields per acre (Amarasingha et al. 2017). Although mungbean has a yield potential of 2.5–3.0 tons per hectare, its actual average productivity is notably low, around 0.5 tons per hectare. This significant disparity is attributed to various factors, including biotic and abiotic stresses, suboptimal crop management practices, and the limited availability of high-quality seeds from improved varieties to farmers (Chauhan et al. 2010; Pratap et al. 2020). Mungbean is best produced in silty loam soil, which maximizes soil nitrogen uptake and plant biomass accumulation (Diatta, Thomason, et al. 2020), but it can suffer under high-salinity

Abbreviations: ANOVA, analysis of variance; LSD, least significant difference; MT, metric ton; USDA, United States Department of Agriculture.

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soils (Ahmad et al. 2014; Barkodia et al. 2017) and waterlogged soil conditions (Kumar et al. 2013). Similar to other legumes, mungbean is high in isoflavonoids, antioxidants, amino acids, minerals, protein (~24% easily digestible protein), and vitamins, which are associated with health benefits such as combating hyperglycemia, hyperlipemia, and hypertension, and it has cancer prevention properties (Akpapunam 1996; Bessada et al. 2019; Hou et al. 2019).

1.1 | Market Potential and Emerging Demand in the United States

In the United States, mungbean serves a niche market in Asian cuisine, where it is commonly used in Chinese and Korean dishes as bean sprouts and in South Asian dishes like mungbean dahl (Fery 2002; Lambrides and Godwin 2007). Because of its key role in Asian cuisines, mungbean is commonly sold in Asian grocery stores across the United States. Despite this demand, the majority of mungbeans sold in the United States are imported from India, China, and Thailand (USDA 2022). Imported mungbeans increased in value from 2.84 million USD in the 2018/19 market year to 6.00 million USD in the 2020/2021 market year, for an 111% increase. In 2020/2021, 36,000 MT of mungbeans were imported, whereas domestic production remained limited at 2600 MT (USDA 2022).

Beyond its role in traditional cuisine, the growing demand for plant-based proteins has significantly boosted mungbean's market potential. Mungbean protein isolate is the primary ingredient in plant-based alternatives such as Beyond Burger and JUST Egg, both of which are widely available in US grocery stores. Demand for plant alternative proteins is expected to continue to increase in the United States as consumers are making a push for more sustainable food options (Havlík et al. 2014). The global alternative protein industry is projected to reach $21.23 billion by 2025 (de Boer et al. 2014), further solidifying mungbean's potential in this expanding sector.

1.2 | Current US Production and Mungbean's Potential in Virginia

Despite significant domestic and international market opportunities, mungbean production in the United States remains limited. The crop is primarily grown in Oklahoma, with smaller acreages in California, Texas, Tennessee, and Kentucky. Breeding efforts to expand mungbean production into the Midwest, including Iowa, are underway (Singh et al. 2021).

A study by Bhardwaj and Hamama (2015) found that mungbean could be a successful crop in Virginia, with yields ranging from 1.15 to 1.47 MT ha^{-1}. The global average mungbean yield is 1.13 MT ha^{-1}, although optimal conditions can produce up to 1.90 MT ha^{-1} (Chauhan and Williams 2018; Thomas et al. 2004). Given its short growth cycle, mungbean presents a viable double-cropping opportunity with winter wheat, offering an alternative to soybean. In Virginia, double-cropped soybeans often suffer reduced yields because of late planting and limited canopy development for efficient light absorption (Holshouser 2014). On the contrary, mungbean could fully mature between winter wheat harvest (late June and early July) and the first frost, making it an attractive alternative for farmers.

1.3 | Declining Tobacco Production and Alternative Crop Considerations

Over the past several decades, US tobacco production has declined significantly because of multiple factors, including public health regulations, shifting consumer preferences, and economic challenges (Cornelius et al. 2022). Since 1965, tobacco consumption in the United States has drastically declined, with cigarette smoking rates dropping from 43% of the population to 18% by 2012 (Warren et al. 2014). In 2020, approximately 19% of adults in the United States reported using at least one type of tobacco product. This includes traditional cigarettes as well as alternative tobacco products such as e-cigarettes, cigars, and smokeless tobacco (Cornelius et al. 2022). This decline in tobacco demand has resulted in a decrease in grown US tobacco, from 931,655 acres in 1982 to 187,630 acres in 2023, reflecting an overall reduction of more than 80% (USDA 2024). Virginia has a long history as one of the leading tobacco-producing states in the United States, with tobacco farming dating back to the colonial era. Tobacco was a primary cash crop that fueled Virginia's economy for centuries, supporting rural communities and agricultural infrastructure (Davis and Mintz 2016). In Virginia, tobacco acreage has plummeted from 53,770 acres in 1997 to 13,070 acres in 2023 (USDA 2024). Since the decline of tobacco, many former tobacco farmers have transitioned to agronomic crops such as corn, soybean, and wheat, as well as specialty crops like hemp (McDonough 2022b).

Given the rising demand for mungbean-based food products and the declining acreage of traditional crops such as tobacco, there is growing interest in expanding mungbean cultivation in the southeastern United States, particularly in Virginia (Bhardwaj and Hamama 2015; McDonough 2022a). This study aims to evaluate mungbean's feasibility as an alternative crop for Virginia farmers, particularly in the context of declining tobacco production. By examining the effects of cultivar selection, planting date, and production management, this research seeks to determine the viability of mungbeans as a high-value specialty crop that could integrate into existing crop rotations and contribute to sustainable agricultural diversification.

2 | Materials and Methods

2.1 | Locations

Field tests were conducted in farmers' fields: Brick Goldman's farm in Cullen in 2021 and Red Handle Farm in Amelia Courthouse in 2022, both located in southern Virginia, and at the Virginia Tech Southern Piedmont Agricultural Research and Extension Center (SPAREC) in Blackstone, VA, each year. Both farms are smaller scale vegetable producers, whereas SPAREC primarily serves as a research station for tobacco and field crop production. Soil type varied across locations and likely influenced mungbean growth and yield. The soil at SPAREC is classified as silty loam, which is well-drained and generally favorable

for legume production. At Goldman Farm, early-planted mungbeans were grown in sandy loam, whereas late-planted plots were located in clayey loam soil, which has a higher water holding capacity and is more prone to waterlogging. The soil at Red Handle Farm was predominantly loam, a balanced texture that retains moisture well but can vary in productivity depending on rainfall and weed pressure.

Soil nutrient status at the SPAREC location was determined via soil testing at the beginning of each season. In 2021, soil pH was 6.11, with 11-ppm phosphorus (P), 61-ppm potassium (K), 235-ppm calcium (Ca), and 76-ppm magnesium (Mg). In 2022, soil pH was 5.82, with 6-ppm P, 126-ppm K, 378-ppm Ca, and 92-ppm Mg. These values reflect moderate variation in soil fertility between the two growing seasons, particularly in phosphorus and calcium levels.

2.2 | Cultivars

Berken and OK 2000, two commercially available mungbean cultivars, were used at multiple locations in Southside Virginia. These mungbean varieties are medium to large with bright green seed coats. Seeds were purchased from the Oklahoma Seed Foundation and inoculated with cowpea *Bradyrhizobia* purchased from Amazon.

2.3 | Experimental Design

Field tests were conducted using a split-block within a randomized complete block design (RCBD), with planting date as the main plot and cultivar as the subplot. At SPAREC, four replications were used to facilitate mechanized seeding. On-farm locations (Goldman and Red Handle Farms) were also arranged as split-block RCBDs, with three or four replications depending on field size constraints. Within each replication, planting dates and cultivars were independently randomized to minimize bias in treatment allocation. Blocking was implemented at all locations to account for field variability. Each block (replication) served to reduce the error associated with environmental gradients such as soil texture, elevation, or moisture retention across the plots. Plots consisted of four rows, each 7.62 m long, with interrow spacing of either 38.1 or 76.2 mm, and a planting depth of 2–3 cm (Table 1). The seeding rate was 95,680 seeds ha^{-1} for 76.2-mm rows and 191,360 seeds ha^{-1} for 38.1-mm rows. Regardless of row spacing, each row contained 56 seeds. Because of field size constraints, Red Handle Farm had only three replications and used 38.1-mm interrow spacing.

2.4 | Field Cultivation and Management

Management practices varied by location, as farmers were primarily responsible for maintaining the mungbean trials.

At SPAREC, the fields were disk-tilled in 2020 and 2021, and 0–6-18 fertilizer was applied at a rate of 50 kg ha^{-1} to prepare the soil. Mungbeans were planted using a four-row soybean planter, and an electric fence was installed surrounding the field to prevent ruminant damage. In 2022, plots were irrigated with 1 in. of water immediately after planting, whereas no irrigation was applied in 2021. To manage weeds, Poast herbicide, a broad-spectrum postemergence grass herbicide, was applied in late July both years at a rate of 1.5 pt. $acre^{-1}$ (1.75 L ha^{-1}). A second herbicide application was made on September 13, 2022, consisting of Poast (sethoxydim) at 1.5 pt. $acre^{-1}$ (1.75 L ha^{-1}), Sharpen (saflufenacil) at 2 oz. $acre^{-1}$ (140 g ha^{-1}), and Twister (methylated ester from vegetable oils) at 2 pt. $acre^{-1}$ (2.34 L ha^{-1}), a low-use-rate crop oil concentrate. Sharpen, a desiccant labeled for use in dry beans, was applied as a harvest aid to facilitate dry-down. However, excessive green foliage persisted after application, requiring hand harvesting in both years. Harvest occurred on September 27, 2022. At Goldman Farm in 2021, field preparation included disking, fertilizing with 19-19-19, and applying pendimethalin (Prowl) preemergence at 4 pt. $acre^{-1}$ (4.67 L ha^{-1}) for weed control. The mungbeans were planted using a hand planter and were rain-fed. Following the seedling emergence of both planting dates, Poast (sethoxydim) was applied at 1.5 pt. $acre^{-1}$ (1.75 L ha^{-1}) to manage grass weeds.

At Red Handle Farm in 2022, the field was tiled, and fertilizer was applied based on soil test recommendations for soybeans. Mungbeans were planted by hand. After plant establishment, the field was hand-weeded periodically until about halfway through the growing season because of higher demands from other crops. Therefore, the second planting date was not hand-weeded as frequently, and the plants suffered from high weed pressure. No herbicides or irrigation were applied throughout the growing season. The plots were hand-harvested at both Red Handle Farm and the Goldman Farm.

2.5 | Harvest and Data Collection

Harvesting was initiated when 75% of the pods had matured, or the green pods had turned completely dark black. To assess yield components, five representative plants were selected from the two center rows, and the following parameters were measured: plant height, pods per plant, seeds per pod, and seed size. Plant

TABLE 1 | Planting dates (PD) and harvest dates (HD) at SPAREC, Goldman Farm, and Red Handle Farm in 2021 and 2022.

	Farm name	Reps	Row space	Early PD	Late PD	Early HD	Late HD
2021	SPAREC	4	76.2 mm	Jun. 2	Jun. 21	Sept. 27	Oct. 4
	Goldman Farm	4	76.2 mm	Jun. 16	Jun. 28	Oct. 4	Oct. 4
2022	SPAREC	4	76.2 mm	Jun. 17	Jul. 1	Sept. 28	Sept. 28
	Red Handle Farm	3	38.1 mm	Jun. 17	Jul. 1	Sept. 14	Sept. 22

height (cm) was measured in the field from the base of the plant to the highest terminal bud. After selecting the five plants, mature pods from the remaining plants in the two center rows were hand-harvested.

Pods per plant were determined by counting the total number of mature pods on all five selected plants and calculating the average. Seeds per pod were determined by selecting ten representative pods from any of the five plants, counting the total number of seeds, and averaging the values. Hundred seed weight (HSW) was measured by weighing 100 seeds from the selected plants. The total seed weight from the five sampled plants was combined with the harvested plot yield for final yield calculations.

2.6 | Statistical Analysis

Statistical analysis was conducted using PROC ANOVA in SAS (version 9.4). Each location was analyzed independently because of differences in field management, planting dates, and harvest dates. Because analyses were conducted independently for each location, the difference in the number of replications (three at Red Handle Farm vs. four at SPAREC and Goldman Farm) did not affect the statistical validity of the tests. Therefore, balanced one-way ANOVA was used without the need for unbalanced ANOVA or mixed model analysis. Fisher's least significant difference (LSD) at a significance level of $p < 0.05$ was used to determine treatment differences. Because each site-year trial was analyzed independently, no combined statistical model was used across locations. Therefore, site-to-site variation was not modeled as a random or fixed effect. Environmental differences such as rainfall, soil type, and weed pressure are discussed in the Results and Discussion sections but were not included as covariates or factors in the statistical model. Although linear mixed models (LMMs) are often used in multienvironment trials to account for hierarchical and repeated measures, their application in this study was not feasible because of substantial differences in planting and harvest schedules across site-years. In some locations, both planting dates were harvested on the same day, whereas in others they were harvested at different times, resulting in variable durations between planting and harvest. This, combined with differences in field management and environmental conditions, introduced potential confounding effects that would limit the validity of a combined analysis. Therefore, each site-year was analyzed independently to maintain the integrity of treatment comparisons within each environment.

3 | Results

3.1 | Yield Performance of Mungbean Cultivars Across Planting Dates and Locations in 2021

In 2021, mungbean yield ranged from 0.35 MT ha^{-1} (OK 2000, early planting) to 1.04 MT ha^{-1} (Berken, early planting), with an average yield of 0.80 MT ha^{-1} (Figure 1) at SPAREC. No significant differences were observed in yield between planting dates or cultivars. However, a significant planting date × cultivar interaction was observed (Table 2). Late-planted Berken outperformed early-planted Berken, and late-planted OK 2000 yielded higher than early-planted OK 2000. This interaction suggests that late planting was more beneficial for Berken, whereas early planting favored OK 2000 (Figure 1).

At the Goldman Farm, yield ranged from 0.47 MT ha^{-1} (OK 2000, late planting) to 1.13 MT ha^{-1} (OK 2000, early planting), with an average yield of 0.88 MT ha^{-1} (Figure 1). Like SPAREC, there were no significant differences between planting dates or cultivars for yield (Table 2). OK 2000 had a large variation in yield for both planting dates, with a standard deviation of 0.15 in early planting and 0.14 MT ha^{-1} in late planting. Berken also showed yield variability in early planting, with a standard deviation of 0.16 MT ha^{-1} (Figure 1). Although early-planted OK 2000 had the highest average yield, followed by early-planted Berken, the variation among replications reduced the certainty of the planting date's effect.

The average yield across planting dates and cultivars was 0.80 MT ha^{-1} at SPAREC and 0.88 MT ha^{-1} at the Goldman Farm. Despite mungbean's drought tolerance, adequate moisture after planting is essential for germination and stand establishment. Soil type also plays a key role, as mungbean is most productive in silty loam soil, followed by sandy loam, and performs worst in clayey soil, which has a higher water holding capacity and is more prone to waterlogging (Diatta, Abaye, et al. 2020). In 2021, SPAREC received 14.2 mm of rain within three days of early planting and 32.5 mm within 2 days of late

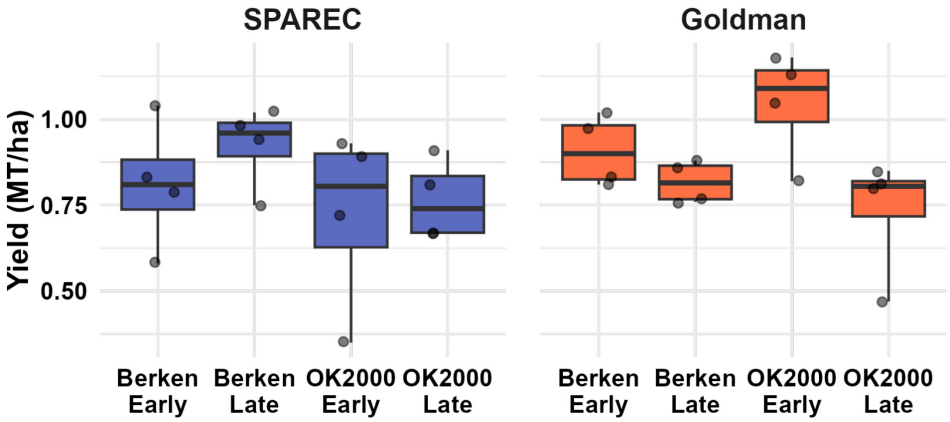


FIGURE 1 | Spread and means of yield data from all OK 2000 and Berken replications in early and late plantings at both locations in 2021.

TABLE 2 | Analysis of variance (ANOVA) for planting date, cultivar, and location effects on yield and yield components in 2021.

Source	df	Yield	Plant ht.	Pods plant^{-1}	Seeds pod^{-1}	100-Seed weight
		——————————————*Pr>f*——————————————				
Southern Piedmont AREC						
Rep	3	0.01**	ns	ns	ns	ns
Plant date	1	ns	0.02*	ns	ns	ns
Rep*Plant date[a]	3	—	—	—	—	—
Cultivar	1	ns	0.03*	ns	ns	ns
Rep*Cultivar[b]	3	—	—	—	—	—
Plant date*Cultivar	1	0.04*	ns	ns	ns	ns
CV (%)		5.27	10.31	16.52	3.06	7.92
Brick Goldman Farm						
Rep	3	ns	ns	ns	ns	ns
Plant date	1	ns	ns	ns	ns	0.02*
Rep*Plant date[a]	3	—	—	—	—	—
Cultivar	1	ns	ns	ns	ns	ns
Rep*Cultivar[b]	3	—	—	—	—	—
Plant date*Cultivar	1	ns	ns	ns	ns	ns
CV (%)		15.43	3.39	28.29	3.42	17.41

[a]Used as an error term for plant date ANOVA.
[b]Used as an error term for cultivar.
*Significant at the probability level.
**Significant at the 0.01 level. ns, nonsignificant at the 0.05 probability level.

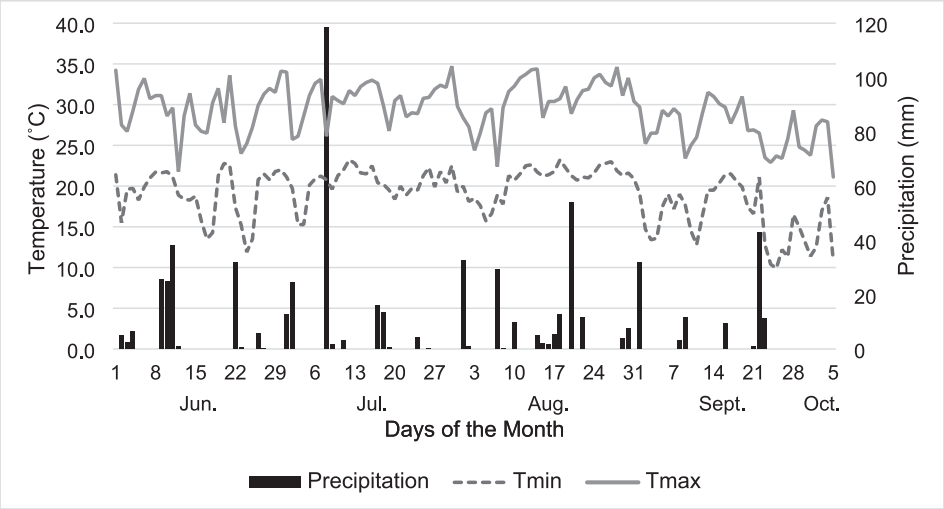


FIGURE 2 | Climatographic based on weather reports from June 1 to October 5, 2021, at Southern Piedmont AREC.

planting (Figure 2). In contrast, Goldman Farm delayed early and late planting by 1–2 weeks and experienced no rainfall until the eighth day postplanting, when it received 32.5 mm of rain. Additionally, late-planted mungbeans at Goldman Farm benefited from 37.1 mm of rain on the third and fourth days postplanting. However, they were grown in clayey loam soil, unlike the early-planted mungbeans, which were established in more favorable sandy loam soil.

3.2 | Yield Performance of Mungbean Cultivars Across Planting Dates and Locations in 2022

At the SPAREC in 2022, yield ranged from 0.20 MT ha^{-1} (OK 2000, late planting) to 0.94 MT ha^{-1} (OK 2000, early planting), with an average yield of 0.46 MT ha^{-1} (Figure 3). Significant differences were observed in the yield between planting dates and cultivars (Table 3). For both cultivars, early-planted ones

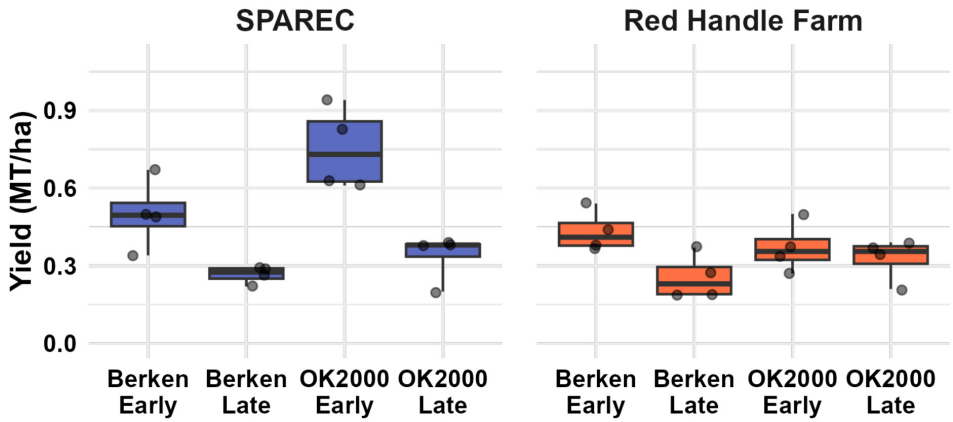


FIGURE 3 | Spread and means of yield data from all OK 2000 and Berken replications in early and late plantings at both locations in 2022.

TABLE 3 | Analysis of variance (ANOVA) for planting date, cultivar, and location effects on yield and yield components in 2022.

Source	df	Yield	Plant ht.	Pods plant^{-1}	Seeds pod^{-1}	100-Seed weight
		——————————————*Pr>f*——————————————				
Southern Piedmont AREC						
Rep	3	ns	ns	ns	ns	ns
Plant date	1	0.02*	0.006**	ns	ns	ns
Rep*Plant date[a]	3	—	—	—	—	—
Cultivar	1	0.03*	ns	ns	ns	ns
Rep*Cultivar[b]	3	—	—	—	—	—
Plant Date*Cultivar	1	ns	ns	ns	ns	ns
CV (%)		28.90	8.86	24.19	7.03	13.00
Red Handle Farm						
Rep	2	ns	ns	ns	ns	ns
Plant date	1	0.05*	ns	ns	ns	ns
Rep*Plant date[a]	2	—	—	—	—	—
Cultivar	1	ns	ns	ns	ns	ns
Rep*Cultivar [b]	2	—	—	—	—	—
Plant date*Cultivar	1	ns	ns	ns	ns	ns
CV (%)		15.19	10.62	44.75	9.77	11.65

[a]Used as an error term for plant date ANOVA.
[b]Used as an error term for cultivar.
*Significant at the 0.05 probability level.
**Significant at the 0.01 level. Ns, nonsignificant at the 0.05 probability level.

outperformed late-planted ones. This interaction suggests that early planting was more beneficial because of the climatic conditions in 2022 (Figure 3).

At Red Handle Farm, mungbean yield ranged from 0.19 MT ha^{-1} (Berken in late planting) to 0.54 MT ha^{-1} (Berken in early planting), with an average yield of 0.35 MT ha^{-1} (Figure 3). The yield at the early planting date was significantly higher than at the late planting date. Similarly to SPAREC, early Berken yielded twice as much as late Berken, whereas OK 2000 yielded 0.05 MT ha^{-1} more in early planting than late planting (Table 3). There were no significant differences between cultivars in overall yield performance.

In 2022, early and late planting for the SPAREC and Red Handle Farm were sown on the same dates. Within the first week of early planting, the fields received 19.6 mm of rain, though most of the rainfall was on days five and six postplanting. In contrast, late-planted fields received less than 2.5 mm of rain in the first week and less than 22.1 mm over 24 days (Figure 4**)**. At SPAREC, both planting dates were irrigated with 25.4 mm of water after sowing, but no further irrigation was needed throughout the

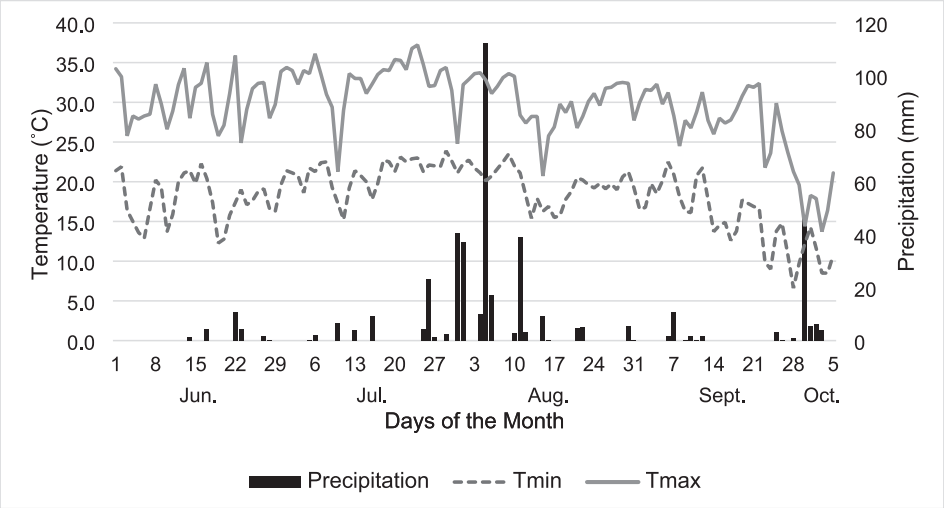


FIGURE 4 | Climatographic based on weather reports from June 1 to October 5, 2022, at Southern Piedmont AREC.

growing season. Red Handle Farm, however, was solely rainfed and did not receive any supplemental irrigation after sowing.

Through observation, it was clear that the late-planted mungbean at both locations in 2022, particularly at Red Handle Farm, appeared stunted for most of the growing season and only showed bulk growth in the last 2 weeks before harvest. In addition, because of reduced maintenance, the combination of drier conditions and increased weed pressure at both locations likely contributed to the lower late-planting yields at both locations. The higher overall yields at SPAREC compared to Red Handle Farm are likely a response to SPAREC irrigation postplanting and the longer growing season. SPAREC plots were harvested 1–2 weeks later than Red Handle Farm because of labor availability and resources, allowing for extended grain filling and development.

3.3 | Plant Height

At SPAREC in 2021, plant height was significantly influenced by both planting date and cultivar. Early-planted mungbean plants grew significantly taller than late-planted ones, and Berken was significantly taller than OK 2000 (Table 2). Although Berken maintained a similar average height across planting dates, OK 2000 was 3.0 cm taller in early than in late plantings (Table 4). In 2022, plant height at SPAREC also differed significantly between planting dates (Table 3), with early-planted mungbeans averaging 8.0 cm taller than late-planted ones (Table 4). This difference was likely due to higher weed pressure and drought conditions followed by excessive moisture during the early vegetative growth stages in the late-planted beans. However, at Goldman Farm in 2021 and Red Handle Farm in 2022, no significant differences in plant height were observed between planting dates or cultivars.

3.4 | Pods Plant^{-1}

Across all locations and years, no significant differences were found in the number of pods between planting dates or cultivars (Tables 2 and 3). However, some locations had noticeably more pods per plant. At SPAREC, the average pod count increased from 51.25 pods per plant in 2021 to 88 pods per plant in 2022. The Goldman Farm in 2021 averaged 67.25 pods per plant, whereas the Red Handle Farm in 2022 recorded an average of 61 pods per plant (Table 4). Because no statistical analysis was conducted across locations or years, these differences can only be noted as observational trends.

3.5 | Seeds Pod^{-1}

The number of seeds per pod was not significantly different between planting dates or cultivars across all locations and years (Tables 2 and 3). In 2021, the average number of seeds per pod was 10.75 at SPAREC and 10.45 at Goldman Farm, with a range of 9.6 to 11.5 seeds per pod across both locations. In 2022, the seed count was slightly higher, averaging 12.1 seeds per pod at SPAREC and 11.9 at Red Handle Farm. Overall, the seed count ranged from 10.7 to 14.2 seeds per pod, with a mean of 12.1 seeds per pod in 2022 (Table 4).

3.6 | 100-Seed Weight

There were no significant differences in 100-seed weight between planting dates and cultivars at SPAREC in 2021 and the Red Handle Farm in 2022 (Tables 2 and 3). However, a significant difference was observed at Goldman Farm in 2021, where early-planted seeds were significantly larger than late-planted seeds (Table 2). Seed weight in 2021 was smallest at SPAREC, averaging 3.9 g per 100 seeds, whereas in the same year it was larger at Goldman Farm, averaging 5.3 g. In 2022, 100-seed weight increased to 5.2 g at SPAREC and 4.7 g at Red Handle Farm (Table 4). Seed size is influenced by both genetics and seed quality, because Berken and OK 2000 have similar genetic seed sizes; seed size variations in this study primarily reflect differences in seed quality. Notably, SPAREC in 2021 experienced a later-than-usual harvest, leading to poorer seed quality characterized by increased mold and wrinkling, which likely contributed to the smaller seed size observed at that location.

TABLE 4 | Average yield components of Berken and OK 2000 in all locations from 2021–2022.

Planting date	Cultivar	Plant ht. (cm)	Pods plant^{-1}	Seeds pod^{-1}	100-Seed weight (g)
2021					
SPAREC					
Early	Berken	44	54	10.7	3.4
Early	OK 2000	36	51	10.4	4.0
Late	Berken	44	55	10.9	3.7
Late	OK 2000	33	45	11.0	4.5
	Average	39	51	10.7	3.9
Brick Goldman Farm					
Early	Berken	28	88	10.4	5.4
Early	OK 2000	24	64	10.5	5.6
Late	Berken	28	57	10.5	5.3
Late	OK 2000	29	60	10.4	4.9
	Average	27	67	10.4	5.3
2022					
SPAREC					
Early	Berken	42	99	13.2	4.8
Early	OK 2000	34	103	11.7	5.4
Late	Berken	32	69	12.4	5.1
Late	OK 2000	28	81	12.0	5.6
	Average	34	88	12.3	5.2
Red Handle Farm					
Early	Berken	40	48	12.2	4.4
Early	OK 2000	39	48	11.6	4.2
Late	Berken	32	65	11.6	5.0
Late	OK 2000	32	83	12.0	5.2
	Average	35	61	11.8	4.7

3.7 | SPAREC Weather Data

Weather data recorded at SPAREC in 2021 and 2022 revealed consistent temperatures between years but significant differences in precipitation. The average temperature from June to September was 23.7°C, with a range of 9.9°C to 34.7°C in 2021 (Figure 2) and an average of 23.7°C, with a range of 6.6°C to 37.2°C in 2022 (Figure 4). Meanwhile, rainfall patterns differed dramatically from June to September in 2021 (Figure 2), which was 193 mm higher than in 2022 (Figure 4), with 625 and 431.5 mm, respectively. Although precipitation was much higher in 2021, it was consistent throughout the summer, with only one dry spell of 10 days with less than 12.7 mm of rain in mid-June and one tropical storm, Elsa, with 118.0 mm on July 8. There were nine heavy rains above 25.4 mm and only 3 days with more than 38.1 mm. Rainfall in 2022, however, was very scarce, with a cluster of heavy rain in midsummer. June went 21 continuous days with less than 12.7 mm of rain and less than 25 mm throughout the month. From July 25 to August 15, there was a total of 302.8 mm of precipitation. This 3-week period accounted for 70% of the entire summer's rainfall. These extreme differences in rainfall patterns likely contributed to the substantial yield decline from 0.83 MT ha^{-1} in 2021 to 0.41 MT ha^{-1} in 2022.

4 | Discussion

Mungbean presents significant potential as an alternative crop for southern Virginia tobacco farmers. In some cases, yields reached as high as 1.18 MT ha^{-1}, which is higher than the global average of 1.13 MT ha^{-1} (Chauhan and Williams 2018; Thomas

et al. 2004) and the 0.5 MT ha^{-1} average in India, the world's largest mungbean producer (Nair and Schreinemachers 2020). Despite high yields under favorable conditions, performance was inconsistent, with yields ranging from 0.19 to 1.18 MT ha^{-1}. The average declined from 0.84 MT ha^{-1} in 2021 to 0.38 MT ha^{-1} in 2022, underscoring year-to-year variability. A similar field trial for the production of mungbean in Piedmont, Virginia, found yields ranging from 1.15–1.47 MT ha^{-1} (Bhardwaj and Hamama 2015), suggesting that Virginia farmers could achieve competitive yields with optimized agronomic practices.

The planting date significantly affected yield in 2022 and plant height at SPAREC in both years, likely due to less precipitation and increased weed pressure in late plantings. These findings underscore the critical role of timely irrigation and effective weed management in optimizing mungbean production across varying planting windows. At SPAREC in 2021, a significant planting date × cultivar interaction was observed, with OK 2000 performing better in late planting and Berken excelling in early planting. This suggests that cultivar selection should be carefully matched to the planting schedule to optimize yields.

Differences in soil texture and field management practices across the three locations likely played a significant role in the observed variation in mungbean performance. At SPAREC, the silty loam soils provided a favorable balance of moisture retention and drainage, which is ideal for legume growth and nodulation. This, combined with the application of fertilizer and timely irrigation in 2022, likely contributed to the relatively higher yields and plant vigor observed at this location, particularly under early planting conditions. In contrast, the Goldman Farm had contrasting soil textures for each planting date: sandy loam for early-planted mungbeans and clayey loam for late-planted mungbeans. Sandy loam soils tend to drain quickly and warm faster in early summer, which may have supported better root development and early growth. However, the clayey loam soils in the late-planted plots likely retained more water but also posed challenges because of reduced aeration and increased risk of waterlogging, to which mungbean is particularly sensitive. At Red Handle Farm, the loam soils offered a balanced texture, but the absence of irrigation and inconsistent weed management, particularly in the late-planted plots, exacerbated stress under limited rainfall, likely contributing to stunted growth and lower yields. Moreover, high weed pressure due to limited manual weeding in the second planting further reduced resource availability for mungbean growth. These site-specific differences emphasize the need to align cultivar selection and planting schedules with local soil characteristics, climate conditions, and available management practices. Future mungbean trials should consider stratifying experimental design by soil texture and testing targeted soil amendments or tillage practices to optimize productivity under different soil regimes.

Beyond yield variability, key obstacles to mungbean production in Virginia include the absence of an established supply chain and challenges related to mechanical harvesting. Although mungbeans can be harvested using combine equipment similar to soybeans, further research is needed to determine the optimal timing for desiccant application, ensuring plants dry adequately without compromising seed quality. Furthermore, Berken and OK 2000 varieties have severe lodging problems in Virginia, making them unsuitable for mechanical harvesting under current conditions. Another critical challenge is the indeterminate growth habit of available cultivars, which complicates harvest timing because of staggered pod maturation. Developing determinant mungbean cultivars could significantly enhance production efficiency.

Despite these challenges, the highest recorded yields demonstrate the mungbean's strong potential in Virginia. Several challenges may be addressed through improved management practices and targeted breeding interventions. Collaboration with extension specialists in agronomy, plant pathology, entomology, and soil science could help establish comprehensive production guidelines tailored to Virginia's growing conditions. Additionally, mungbean integrates well into Virginia's crop rotations with winter wheat but requires intensive management similar to vegetable crops to maximize profitability. Breeding programs could benefit from publicly available germplasm from the World Vegetable Center, which maintains 6700 mungbean accessions (Schafleitner et al. 2015). Investment in mungbean breeding has shown substantial economic returns; for example, Myanmar achieved an estimated return of $92 for every dollar invested in mungbean breeding since 1980 (Sequeros et al. 2020). Similarly, strategic investments in mungbean development for southern Virginia have the potential to have large economic returns, offering tobacco farmers a viable alternative crop with strong market potential.

Although LMMs can be a more statistically robust approach for analyzing multi-environment data, we determined that they were not appropriate for this dataset because of substantial differences in planting and harvest timing, as well as management practices among locations and years. In some environments, both planting dates were harvested on the same day, whereas in others, harvest occurred at different times, creating variation in the duration between planting and harvest that could confound treatment effects in a pooled model. Additionally, location-specific factors such as irrigation, weed control, and soil type introduced heterogeneity that could not be adequately modeled given the available replication and design structure. As a result, each site-year was analyzed independently using one-way ANOVA to identify treatment effects within individual environments. We acknowledge that this approach does not allow for formal estimation of environment-level variance components, limiting generalizability. Future experiments will be designed with harmonized management protocols and schedules to enable LMM analysis and stronger cross-environment inference.

By strategically addressing agronomic challenges, optimizing mechanization techniques, and advancing breeding efforts to develop high-performing, regionally adapted cultivars, mungbean has the potential to become a profitable, resilient, and sustainable crop option for Virginia farmers. The ability to achieve yields exceeding global and Indian averages under optimal conditions demonstrates its strong agronomic potential, whereas the challenges observed, such as yield variability, lodging issues, and the need for improved weed and irrigation management, highlight key areas for refinement. By investing in research, developing best management practices, and fostering supply chain infrastructure, Virginia farmers could capitalize on mungbean as a high-value alternative to traditional crops like tobacco,

ensuring economic stability, crop diversification, and long-term agricultural sustainability in the region.

5 | Conclusion

This study demonstrates that mungbean [*Vigna radiata* (L.) R. Wilczek] holds strong potential as an alternative specialty crop for tobacco farmers in southern Virginia. Under favorable conditions, yields exceeded global and Indian averages, highlighting its agronomic promise. However, significant variability across sites and years, driven by differences in soil type, rainfall patterns, planting dates, and management practices, underscores the need for optimized production strategies, including timely irrigation, weed control, and appropriate cultivar selection.

The performance of Berken and OK 2000 varied with planting date and location, indicating that future efforts should prioritize breeding regionally adapted, determinate cultivars with enhanced lodging resistance and synchronous maturity to support mechanized harvesting. Additionally, mungbean's adoption will depend on building supply chain infrastructure and market access, particularly as demand grows in both traditional ethnic markets and the plant-based protein sector.

Overall, our findings indicate that early planting was generally more favorable than late planting, particularly under the drier conditions of 2022. At SPAREC, early-planted OK 2000 achieved the highest yield (0.94 MT ha^{-1} in 2022), whereas at Red Handle Farm, early-planted Berken performed best (0.54 MT ha^{-1}). In 2021, cultivar performance varied by location, with early-planted OK 2000 producing the highest yield at Goldman Farm (1.13 MT ha^{-1}) and Berken excelling under late planting at SPAREC (1.04 MT ha^{-1}). Taken together, these results suggest that early planting generally confers an advantage in Virginia, with OK 2000 showing greater consistency across environments, whereas Berken may perform competitively under specific site-year conditions. Thus, although both cultivars demonstrated potential, early planting of OK 2000 appears to be the most reliable option under current Virginia growing conditions.

With investment in production systems and stakeholder collaboration, mungbean could offer a profitable, resilient, and sustainable alternative to declining tobacco acreage, supporting economic diversification and long-term viability for Virginia farmers.

Author Contributions

Jessica Wilbur: conceptualization, investigation, methodology, supervision, data curation, writing – original draft, writing – review and editing. **Matheus Ogando do Granja:** data curation, formal analysis, investigation, visualization, writing – original draft, writing – review and editing. **Lucy Lysek:** investigation, methodology, supervision, data curation. **Eric P. Beers:** conceptualization, investigation, methodology, supervision, writing – original draft. **Carol Wilkinson:** methodology, supervision, data curation, writing – review and editing. **M. Luciana Rosso:** writing – review and editing. **Bo Zhang:** conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, writing – original draft, writing – review and editing. **A. Ozzie Abaye:** conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, writing – original draft.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available because of privacy or ethical restrictions.

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