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Mungbeans: a climate-resilient crop for diversifying Wyoming cropping systems

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Mungbean (*Vigna radiata* L. Wilczek) is a drought tolerant and early maturing legume species with capacity for high seed yield, making it a promising alternative among the limited warm season legume options currently utilized across the Mountain West. Despite its potential for yield and suitability in cover crop mixtures, mungbean has not been systematically evaluated for its performance under Wyoming's agroecological conditions. Semi-arid weather conditions in Wyoming, including low annual precipitation, extreme temperatures, and frequent drought, limit crop productivity. As a drought-tolerant crop, mungbean offers a competitive advantage among the limited warm season legume options available in this region. Its inclusion in Wyoming's semi-arid agroecosystem offers multiple benefits, including crop diversification, an affordable protein source for both livestock and humans, and improved soil health. This review aims to assess the potential for integrating mungbean into dryland and irrigated cropping systems in the Mountain West, emphasizing agronomic performance, economic sustainability, and alignment with existing production systems.

KEYWORDS
alternative crops, cover crop, forage, mountain west, warm season legumes, Montana

1 Introduction

In South and Southeast Asia, mungbean (*Vigna radiata* L. Wilczek) is commonly known as green gram because of its green seed colour and the regional translation of the Hindi term *dal*, meaning edible pulses into the English word gram. It is believed to be native to the Indian subcontinent and domesticated over 4,000 years ago (Zukovskij, 1962). Although mostly referred to as green gram, its seed colours vary from green to brown, and some known yellow tropical varieties. Mungbean belongs to the *Fabaceae* family and are mainly grown for their edible seeds and young sprouts. It is a warm climate and short season legume crop widely cultivated in several continents from Asia to Africa, South America, and Australia. In the United States, it was cultivated in the early 1830's as Chickasaw pea with peak production in the 1940's during the World War II trade blockades from the Asian continent (Oplinger, 1990). In Oklahoma, one of the earliest regions of the U.S. to grow mungbean, production peaked at approximately 35,000 acres to meet U.S. consumption demand needs during WWII, made possible by a grain grower named Dale H. Johnson, who was able to encourage doubting farmers to go into mungbean cultivation in the Garfield county region of the state (Staten, 1942). The majority of U.S. mungbean cultivation and production is largely based in Oklahoma, with few acres grown in Kansas, California, Kentucky, and Texas (Sandhu and Singh, 2020). The nearest evaluation of mungbean to Wyoming was conducted in Montana, about a decade ago, where only two varieties were tested.

Historical mungbean breeding efforts in the U.S. began before 1914, when the U.S. Department of Agriculture (USDA) introduced and evaluated diverse mungbean germplasm from different countries in the field resulting in the selection and release of three cultivars "Berken," "Oklahoma12" and "Kiloga" in 1963 (Matlock and Oswalt, 1963). The 1972 International Mungbean Nursery (IMN) organized by the University of Missouri coordinated the growth of nursery programs at ten locations in Canada, Colombia, Ethiopia, Korea, Thailand and the U.S., with the objectives of providing information on the range in adaptation of the mungbean crop, the specific adaptation of individual cultivars, and characteristics of mungbean plant affecting adaptation (Poehlman et al., 1974). Twenty-eight strains from India (14), Korea (4), Iran (2), Afghanistan (2), Taiwan (1), China (1), Peru (1), unknown (1) and two from the U.S. (Oklahoma12 and Texas Jumbo) were evaluated for yield, flowering, days to maturity, and plant architecture (Poehlman et al., 1974). Thereafter, such coordinated breeding trials have been coordinated by the World Vegetable Center (WorldVeg) in Taiwan, formerly called the Asian Vegetable Research and Development Center (AVDRC).

In Wyoming, decades of reliance on a limited number of forage and feed crops such as hay, alfalfa, and feed barley have enhanced productivity, but often at the expense of agricultural sustainability and nutritional diversity. Agriculture in Wyoming primarily supports its extensive livestock industry, particularly cattle and sheep. Hay represents the most widely cultivated crop in terms of both acreage and production value, while alfalfa remains a preferred forage legume due to its high protein content and superior feed quality. Barley and corn are predominantly grown for animal feed, with portions utilized as grain or processed into corn silage (Wyoming Agricultural Statistics, 2024). Beyond the feed sector, Wyoming produces a limited range of crops for commercial processing and direct human consumption. These include sugar beet, a major cash crop, winter wheat, which is processed into flour for the broader food industry, and dry edible beans such as pinto and navy beans (Coupal and Nagler, 2021).

Overall, Wyoming's agricultural system is heavily dominated by forage and feed crops, highlighting the need to diversify production systems through the inclusion of crops for human consumption and cover cropping. The adoption of cover crops in Wyoming presents an opportunity to improve soil fertility, enhance soil health, and promote long-term agricultural sustainability. However, suitable legume options remain limited due to the challenging climatic conditions of the Intermountain West. Wyoming's high elevation ranking as the second-highest mean elevation in the U.S. results in a short growing season, typically ranging from 60 to 140 frost-free days. This significantly constrains the cultivation of many conventional U.S. crops that require extended warm season conditions.

Modern approaches to agricultural sustainability emphasize the integration of new specialty crops that can complement existing systems dominated by corn, soybean, and traditional cover crops. Wyoming's semi-arid environment, characterized by low annual precipitation, elevated temperatures, and frequent drought stress (EPA, 2016), further limits crop productivity. These conditions particularly affect warm season legumes such as soybean and dry bean (e.g., pinto), which exhibit low drought tolerance and are generally drought sensitive crops. Introducing a new warm season specialty crop such as mungbean, known for its heat and drought tolerance offers a promising alternative. Mungbean has the potential to integrate into existing farming systems, align with current management practices, and provide complementary market opportunities with minimal additional economic burden. Although limited evaluations have been conducted in the neighbouring state of Montana (Henning and Kilian, 2017), a key constraint to advancing mungbean production in Wyoming and the Intermountain West is the lack of a well-characterized germplasm panel adapted to the region.

1.1 Plant description and growth habit

Mungbean is a diploid, self-pollinating, early maturing and short duration warm season legume, typically grown in late May into early June. It exhibits wide adaptability to diverse agroecological conditions with minimal input requirements (Nair et al., 2015). Mungbean plants possess a well-developed and sturdy tap root system that enhances atmospheric nitrogen fixation into the soil through symbiosis with rhizobium thereby replenishing soil fertility and sustaining productivity (Favero et al., 2021). They grow erect or prostrate and can reach up to 1.5 m in length and bare clusters of yellow flowers.

Immature pods or young sprouts are generally greenish in appearance. At maturity, pods turn dark brown and are 0.9 to 1.2 m long. They can hold between 10 to 20 seeds per pod with variation in seed colour ranging from mostly green (Figure 1) to yellow, brown, and mottled green (Oplinger, 1990; Encyclopaedia Britannica, Inc, n.d.; Iowa State University Extension and Outreach, n.d.).

1.2 Mungbean origin, distribution, and diversity

Earliest reports of mungbean domestication are traced to the Indian subcontinent (Vavilov, 1926). Vavilov's theory of mungbean origin has been thereafter supported by a series of studies on morphological diversity (Singh et al., 1974), wild and weedy species distribution and types (Chandel, 1984; Paroda and Thomas, 1988), and archaeological remain evidence (Jain and Mehra, 1980) of mungbean in India. Mungbean is widely cultivated all through South and Southeast Asia, while its wild forms are widely distributed across Central and East Africa, Madagascar, and expanding through Asia and New Guinea, and to Northern and Eastern Australia (Tateishi, 1996). It is not a very popular legume in Africa when compared to cowpea and is one of the least known legumes in the United States. Most of the U.S. mungbeans are grown in Oklahoma as grain for use in several food products and sometimes ploughed into the soil as green manure. South Asia ranks top in the major mungbean producing regions of the world, with countries like Myanmar and India, producing 1.597 Mt. and 1.6 Mt. respectively (Nair et al., 2020).

Major production has also expanded to regions such as East Africa and Australia (Figure 2). The global distribution of mungbean further highlights its broad adaptability across diverse agroecological conditions. Optimal production environments are typically tropical, with temperatures ranging from 25 to 35 °C and moderate precipitation of approximately 400–550 mm over its 60–90 d life cycle (Singh et al., 2017). In comparison, Wyoming receives annual precipitation of approximately 250–500 mm and experiences average temperatures of 25–32 °C during the June–August growing season (Wyoming State Climate Office and Wyoming Water Resources Data System, 2023). These conditions, fall within the range of climatic requirements for mungbean production. Mungbean is generally considered day-neutral and can reach maturity in as little as 55 days when average temperatures exceed 20 °C (Clarry, 2016; Batzer et al., 2022a; Batzer et al., 2022b). High-yielding cultivars typically require 85–90 days from



FIGURE 1
Mungbeans. **(A)** Flower, photo credit: CABI compendium. **(B)** Leaves and fresh pods, photo credit: Australian mungbean association. **(C)** Dry and mature pods, photo credit: It_man_47. **(D)** Seeds, photo credit: World Vegetable Center.

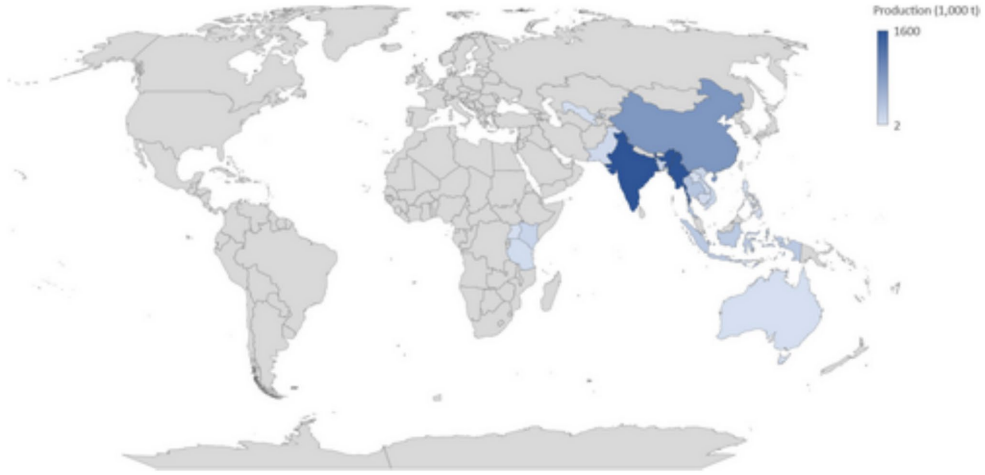


FIGURE 2
Global mungbean production (Nair et al., 2020).

sowing to harvest (Mehandi et al., 2019), while traditional cultivars may take 90–110 days to reach maturity (Humphry et al., 2003). Wyoming typically has a frost-free period of approximately 90–120 days, depending on location. Its high elevation and generally clear skies provide strong solar radiation, which is favourable for mungbean photosynthesis and biomass production.

1.3 Common forage and legume crops of Wyoming agriculture

Alfalfa is the most economically significant crop grown in Wyoming, ranking highest both in total acreage planted and revenue generated (Table 1). Corn, primarily cultivated for silage and haylage, plays a substantial role in Wyoming's agricultural output, reflecting the state's strong dependence on cattle ranching and livestock production. In 2024, approximately 182, 109 ha were planted exclusively to alfalfa, yielding about 3.71 t/ha (Wyoming Agricultural Statistics, 2024). The largest acres grown and harvested after alfalfa were wheat (36, 818 ha), grain corn (26, 305 ha), and barley (20, 655 ha). Other high-value commercial crops grown in smaller production pockets include sugar beet (*Beta vulgaris* L.), barley (*Hordeum vulgare* L.), and wheat (*Triticum aestivum* L.).

Grasses such as barley (*Hordeum vulgare* L.) and oats (*Avena sativa*), along with legumes such as dry bean (*Phaseolus vulgaris* L.), field pea (*Pisum sativum* L.), clover (*Trifolium repens* L.), and vetch (*Vicia sativa*), are also cultivated in various intercropping systems. In 2021, Wyoming produced a significant amount of edible dry bean amounting to $14,364,000 from 6,354 harvested hectares (Coupal and Nagler, 2021). Wyoming is a difficult terrain to grow any crop due to several reasons, which include but are not limited to, water shortage, elevation, frost, hail, and other forms of natural disasters associated with semi-arid northern regions of the U.S. These constraints underscore the need to explore new and emerging crops capable of producing reliable seed yields for human consumption or serving as viable alternatives for forage production and inclusion in cover-crop mixtures. Cool season legumes of Wyoming include field peas, dry bean, vetches and clovers.

TABLE 1 Crops harvested, yield, production and value of production in USD.

Commodity	Harvested (ha)	Yield	Production	Value of production (USD)
Alfalfa	182,109	3.71 t/ha	612, 370 m/tons	85,725,000
Corn, grain	26, 305	9.72 t/ha	255, 900 m/tons	58,311,000
Corn, silage	6, 070	57.06 t/ha	313, 000 m/tons	
Barley	20, 655	6.02 t/ha	124, 200 m/tons	34,414,000
Wheat	36, 818	2.10 t/ ha	76, 700 m/tons	14,669,000
Sugar beets	12, 465	76.0 t/ha	859, 000 m/tons	

However, these legumes are not heat and drought tolerant like the two species of the *Vigna* genus, mungbean (*Vigna radiata*) and cowpea (*Vigna unguiculata*). Mungbean demonstrates superior drought tolerance relative to commonly grown warm season legumes such as soybean and pinto bean, making it a promising alternative for water-limited environments like Wyoming.

2 Benefits of promoting mungbean as a new crop in Wyoming

2.1 Plant diversity in dryland cropping systems

The short, dry, and often extreme summer temperatures of Wyoming (Wyoming State Climate Office and Wyoming Water Resources Data System, 2023) which is characteristic of the semi-arid regions of the U.S., makes it especially difficult to grow much of anything, thus drastically narrowing the diversity of crops species that could be grown in this region. With summers been relatively warm and short, accompanied with high gusty wind almost all year round, the over reliance on only a few crops may pose a greater risk for agriculture in the region affecting food and nutritional security of both humans and livestock due to unpredictable weather conditions. Highly processed bulked grains commonly produced in this region such as wheat and corn, often provide lower nutritive value when compared to other diverse grain and pulse crops (FFAR, 2022). Incorporating mungbean as an alternative grain legume either for direct consumption or within warm season cover crop mixes could enhance both the nutritional quality and crop diversity of production systems. Expanding crop diversity within Wyoming's cropping system which is largely forage and grasses based to include more legumes is necessary for improving resilience, productivity and long-term sustainability, as diversified systems are better equipped to buffer environmental stress. Increased plant diversification supports through incorporation of mungbeans in crop rotational programmes can assist in the suppressions of pest and diseases by interrupting specific host continuity, thereby lowering the spread of pathogens.

2.2 Health and nutritional benefits for both human and animal consumption

Although quite a few people in the U.S. are familiar with this crop mainly due to its use for bean sprouts in salad, many of them have not seen the crop nor do they know where or how it is grown (Iowa State Univ. extension outreach). Mungbean sprouts and seeds are good sources of protein (20–30%) and carbohydrates (60–70%) on a dry weight basis and provide approximately 3,400 kJ energy/kg grain, including some calcium, phosphorus and vitamins (Oplinger, 1990; Pataczek et al., 2018; Somta et al., 2022).

Compared to mungbean, soybean (*Glycine max*) has a substantially higher protein content (approximately 36–40%) and lipid concentration (18–20%), but lower carbohydrate levels, making it energy-dense and oil-rich (USDA, 2023; Messina, 1999). In contrast, dry beans such as pinto and navy bean (*Phaseolus vulgaris*) typically contain 20–25% protein and higher carbohydrate content (55–65%), like mungbean, but generally lower fat content and slightly lower digestibility due to antinutritional factors (Broughton et al., 2003; USDA, 2023). Mungbean is a cheap source of protein and more affordable than meat, and a rich source of amino acids, which could be beneficial to low-income households and the American diets in general (FFAR, 2022). In comparison with other legumes like chickpea, pigeon pea, and lentils, mungbean is more easily digestible and contains lower levels of flatulence-inducing oligosaccharides, enhancing its suitability for human diets (Srivastava and Ali, 2004; Somta et al., 2022), and it is rich in iron and contains lower phytic acid than pigeon pea and soybean (Chitra et al., 1995; Imtiaz et al., 2011). Processed seeds can be fed to livestock as feed while straw or whole plants can be made into haylage (Mogotsi, 2006; Pataczek et al., 2018). Mungbean can be grazed directly by livestock in the fields as forage. Protein content of 13–21% and 9–12% in fresh mungbean forage and straw, respectively, has been reported, which are higher than contained in cereal straw (Sharasia et al., 2017).

2.3 Pastureland and environmental health improvement

The productivity and efficiency of pastureland can be improved using crop mixtures to increase light capture over pure crop stands (Frankow-Lindberg and Wrage-Mönnig, 2015), and it has been established that mixed pastures have a higher nutritive and crop biomass than pure stands (Deak et al., 2007; Acharya et al., 2013; Sturludóttir et al., 2014), thus lost or depleted pasture land in Wyoming could be rejuvenated through the introduction of new and diverse crop species like mungbean into the already existing crop mixes. Legume crops also help improve the fertility and health of grassland soils through nitrogen fixation because of their symbiotic relationship with rhizobia by fixing atmospheric nitrogen into the soil (Giller, 2001; Smith et al., 2016). In grass-legume pastures, atmospheric nitrogen fixation of between 100 to > 500 kg N ha^{-1} $yr.^{-1}$ have been reported (Ledgard and

Steele, 1992; Lüscher et al., 2014). Also, the use of legume-grass combination in pasture management have been reported to suppress weed invasion in mixed farming systems relative to monocropping systems (Deak et al., 2007; Picasso et al., 2008; Sturludóttir et al., 2014; Brink et al., 2015).

The negative effects of N fertilizer application to the environment either through run-off from irrigated fields into water bodies or via the emission of nitrous oxide (N_2O) into the atmosphere can be reduced to a greater extent through legume-based cropping systems. The use of legumes in rotation systems or mixed cropping lowered N_2O emissions in comparison to fertilized annual cropping systems (Mackenzie et al., 1997; Gregorich et al., 2006). Legumes when used in monocropping, intercropping or in rotation, can reduce carbon footprint values and lower N_2O emissions, indicative of the positive inclusion of legumes in cropping systems (Nielsen et al., 2016; Khatiwada et al., 2020). Legumes also improve the below ground microbiome by increasing the availability of N-enriched litter for soil microorganisms which invariably improves the overall soil health. These expanded benefits of integrating highly nutritive legumes into mixed pastures could enhance Wyoming's pasturelands in ways that are not yet fully understood.

2.4 Cattle selectivity and grazing preferences for forage legumes

It has been observed that cattle seem to prefer legumes over grasses. In one study, when presented the choice between alfalfa and tall fescue (*Festuca arundinacea*) monocultures grown in adjacent plots, beef steers showed partial preference for alfalfa (62.5%) (Boland et al., 2011). Other studies have also shown cattle preference for clover over grasses by approximately 70% (Rutter, 2006), and least preference for tall fescue in separate monocultures strips of sainfoin and alfalfa (Villalba et al., 2015). Cattle also exhibited preference for clover silage and their associated mixtures over ryegrass silage (*Lolium perenne* L.) in an experiment looking at eating habits among dairy cows (Dorland et al., 2008). Again, higher intake of clover over grass was recorded in cattle feeding behaviour when both species were spatially grown in mixed or separate monocultures (Rutter, 2006). Studies in the U.S. Southern Great Plains have demonstrated the potential of short-duration summer legumes, including mungbean, to function as high-quality forage crops under semi-arid conditions similar to Wyoming. Although direct use of mungbean in forage trials in Wyoming remain limited, prior research on analogous warm season legumes confirms that short-duration, drought-tolerant species can generate substantial forage biomass and support livestock performance (Eberle and Shortnacy, 2021). Together with broader Great Plains evidence on annual forage legumes, these findings suggest that mungbean is a promising candidate for integration into Wyoming forage and crop-livestock systems. These species provide improved crude protein and digestibility relative to traditional warm season grasses and can fill critical late-summer forage gaps in livestock systems (Baath et al., 2023). Integration of mungbean into forage legumes in Wyoming dryland systems could enhance system and animal productivity.

2.5 Economic significance and market opportunities

Mungbean is among the most important pulse crops cultivated across diverse agro-ecological zones worldwide and is currently grown on approximately 6 million hectares globally (Mota et al., 2021; Chauhan and Williams, 2018). Rising global demand for mungbean, along with escalating market prices, has driven an increase in commercial production and established mungbean as a profitable legume crop worldwide (Keatinge et al., 2011). The first quarter of 2021 saw a 62% increase of mungbean imports into the U.S. in comparison to 2020 imports (NASS, 2021; Batzer et al., 2022a; Batzer et al., 2022b). Approximately 31 million kg of mungbean equating to about $45 million were imported in 2021 from China into the U.S. (NASS, 2021).

In developed countries such as Australia, mungbean valued at $180 million, cultivated on 125,000 ha in 2016, was exported to markets in Asia, Europe, North America, and the Middle East (Clarry, 2016; AMA, 2020). The rising global demand for mungbean, coupled with increasing demand for warm season legume options in Wyoming and Montana (Henning and Kilian, 2017) for forage or cover crop mixes, combined with the increased consumption of mungbeans in America as a plant-based protein alternative, presents a significant opportunity for Wyoming farmers to engage in mungbean cultivation as a profitable cash crop. Wyoming farmers could also benefit from increasing their narrow crop base through the introduction of mungbean, a warm season legume which could serve as a buffer for the numerous economic risks already associated with unpredictability of weather which affects crop production in the region. However, mungbean as a new crop could also face economic risks, including market instability, weak value chains, and producer risk aversion due to limited knowledge of cultivation and management practices. Regional feasibility may also be constrained by semi-arid climate, infrastructure, and institutional support systems. Therefore, successful introduction of mungbean as a new cash crop in Wyoming will require synchronized progress in breeding (adaptation), agronomy (management practices), and market development (value chain systems), rather than agronomic improvement alone.

3 Mungbean germplasm acquisition and introduction

AVRDC—The World Vegetable Centre holds more than 6,700 mungbean accessions, with a well-established and derived minicore collection of 296 accessions. The minicore has well curated phenotypic and genotypic data that captures and represents the diversity of the entire germplasm in the repository of the AVRDC[1] (Schafleitner et al., 2015). The overall idea of a minicore collection is to help reduce costly, laborious and painstaking screening of large collections of germplasm for superior traits of interests which could take decades to accomplish. The minicore collection contains substantial allelic diversity and represents a meaningful subset of the core collection of 1,481 accessions. The core collection was previously developed by randomly selecting 20% of accessions from the entire mungbean germplasm following geographic stratification and cluster analysis based on phenotypic descriptors. Early maturing and drought tolerant varieties, with prostrate or upright type growth habits have been identified by researchers of the International Mungbean Improvement Network (IMIN) established in 2016.[2] Through extensive testing and screening of

1 http://203.64.245.173/

2 https://avrdc.org/intl-mungbean-network/

mungbean germplasm in several countries across Asia and Africa, new genetics has been identified with high grain yield, improved resistance to yellow mosaic virus, salt and heat tolerance along with a wide variation in iron and protein content (Nair et al., 2020). Mungbean genotypes show variability in morphological characteristics ranging from pod positions, seed colour, and curvature of mature pods (Figures 3–6) (Rahangdale et al., 2023).

USDA Mungcore - The USDA Plant Genetic Resources Conservation Unit in Griffin, Georgia, maintains a repository of 4,230 mungbean accessions collected from at least 42 countries worldwide. Mungbean core collection comprising 409 genotypes has been developed to capture the genetic diversity represented within the entire genebank collection. The minicore and mungcore germplasm subset collections from AVRDC and USDA repositories, respectively, may harbor valuable alleles that could enhance adaptation to the dryland climates of Wyoming, therefore evaluating these genotypes under Wyoming environmental conditions is of paramount importance. Extensive use of these available genomic resources from reputable genebank repositories in coordinated breeding programs targeting mungbean adaptation to Wyoming could establish mungbean as a successful warm season legume.

3.1 Evaluation and characterization of mungbean accessions

Reports and literature on the introduction and evaluation of mungbean varieties in Wyoming and Montana are limited. A 2016 study conducted by Henning and Kilian at the USDA Plant Materials Center in Bridger, Montana, evaluated two mungbean varieties, Berken and OK2000, which were developed and released by Oklahoma State University (OSU) through the Oklahoma Agricultural Experiment Station (OAES), with collaborative involvement of USDA scientists, in 1962 and 1999, respectively. These mungbean varieties, along with four cowpea varieties, were assessed to identify suitable warm season legume species for cover crop mixtures in Montana (Figure 7). Despite the poor soil structure of the study area, all evaluated varieties exhibited excellent vigour and overall plant health. Significant differences were observed among varieties for days to 50% flowering and plant height (Table 2). The mungbean varieties flowered earlier than the cowpea varieties, while biomass production did not differ significantly between mungbean and cowpea varieties.

Notable limitations of the study included the evaluation of a limited number of genotypes, assessment of only a few agronomic traits, and the lack of multi-location and multi-year testing of the selected varieties. To overcome some of the limitations associated with this study, there is need to expand evaluation within these regions using more and new mungbean germplasm like the AVRDC mungbean minicore or USDA mungcore subsets, alongside the OK2000 and Berken varieties which are dated back to the 1960's and 1990's earlier attempt at improving mungbean genotypes in the U.S. Thorough



FIGURE 3
Position of mungbean pods in plant; **(A)** below canopy; **(B)** intermediate; **(C)** above canopy.

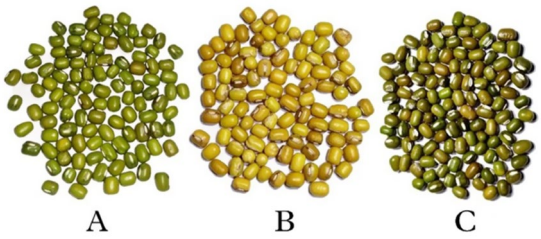


FIGURE 4
Mungbean seed colour. **(A)** Green. **(B)** Yellow. **(C)** Dark green.

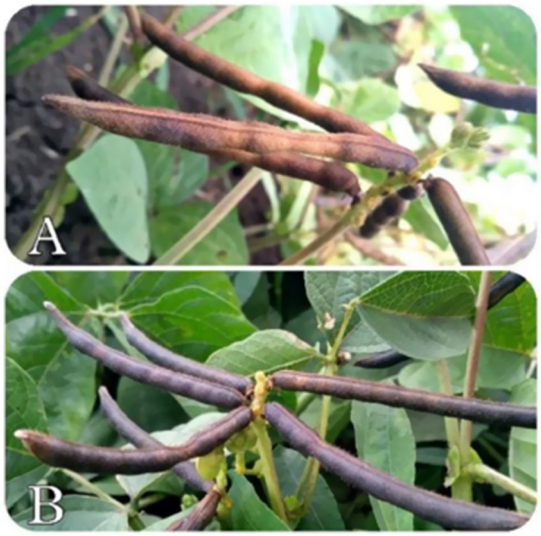


FIGURE 5
Mature pods colour. **(A)** Brown. **(B)** Black.



FIGURE 6
Curvature of mature pods; **(A)** straight; **(B)** curved. Photo credit: (Rahangdale et al., 2023).



FIGURE 7
Test plot of two mungbean and four cowpea varieties at BPMC, Bridger, MT (2016). Photo credit: (Henning and Kilian, 2017).

TABLE 2 Mean days to flowering, mean height of cowpea and mungbean varieties, Bridger PMC, Bridger, MT.

Varieties	DFF	HT (m)	BM (kg/ha)	PH
Red rippers (cowpea)	77 [a]	0.42 [bc]	3,208 [a]	Prostrate
Chinese red (cowpea)	72 [b]	0.48 [b]	4,300 [a]	Upright
OK2000 (mungbean)	68 [b]	0.39 [c]	2,713 [a]	Upright
Berken (mungbean)	68 [b]	0.31 [d]	2,907 [a]	Upright
Black stallion (cowpea)	DNF	0.42 [bc]	1825 [a]	Upright
Iron and clay (cowpea)	DNF	0.55 [a]	4,189 [a]	Upright

DFF (days to 50% flowering); HT (mean height); BM (mean biomass) and PH (plant habit). Means in columns followed by different letters are significantly different according to Tukeys' HSD at $p < 0.05$.

characterization and evaluation of the mungbean minicore or USDA mungcore germplasm through well-replicated, multi-locational experimental trials across Wyoming could facilitate the identification of promising accessions possessing desirable traits such as high grain yield, long pods, large seeds, resistance to biotic and abiotic stresses, suitable adaptation and varying maturity for different cropping seasons. Future trials should be designed over multiple seasons, and priority should be given to the identification of early maturity, photoperiod insensitive, combined heat-drought, and cold tolerance, alongside traits associated with biomass production and forage quality.

Given the integration of crop-livestock systems in the region, the development of dual-purpose cultivars with improved regrowth capacity and high nutritive value will also be essential. Multi-environment testing across Wyoming research stations and the integration of genomic selection, high-throughput phenotyping tools such as near-infrared spectroscopy (NIR), and use of unmanned aerial vehicles (UAVs) mounted with sensors to capture and measure difficult traits will further accelerate genetic gain for adaptation and yield under semi-arid conditions.

4 Enhancing mungbean adaptation to the Wyoming agroecosystem

The limitations of prior single-location and single-season evaluations highlight a critical gap in understanding the adaptive capacity of mungbean under the highly variable and stress-prone environments of the Mountain West, particularly Wyoming. Unlike the Montana study, which provided preliminary insights into establishment and general plant performance, a more integrative framework that captures genotype, environment, and stress interactions are required to inform breeding and management decisions. Evaluating diverse germplasm under both field and controlled conditions will enable the identification of stress-resilient genotypes and key adaptive traits, particularly those conferring tolerance to heat, terminal drought, and early-season frost events common in Wyoming. Moreover, assessing individual and combined stress effects across phenological stages will provide a more realistic representation of field conditions, where crops are rarely exposed to a single stress in isolation.

Such an approach not only strengthens the biological understanding of mungbean adaptation but also establishes a foundation for targeted breeding strategies and the development of climate-resilient cultivars suited to semiarid agroecosystems. The following paragraphs will examine the influence of some abiotic and biotic stressors on mungbean growth, productivity, and yield potential. To our knowledge, no studies have independently evaluated these stressors or their

combined threefold effects at any phenological stage in a Wyoming mungbean trial.

4.1 Implications of heat stress

Over the last century, Wyoming's climate has warmed up by approximately—17.2 °C to −16.1 °C and it is predicted that by 2050, it would become common to have more days where the daily temperatures would go beyond 37.8 °C (EPA, 2016). Wyoming's rising temperatures and drier soils present new challenges to mungbean yield, although mostly grown in warm climates of the world (Chauhan et al., 2017). Temperature periods of above 40 °C greatly impacts flowering and pod development leading to poor growth and yield (Rachaputi et al., 2019). Heat stress from prolonged exposure to high temperatures during flowering can cause up to 90% flower abscission in subtropical legumes (Kumari and Varma, 1983; Heindl and Brun, 1984; Saitoh et al., 2004; Rahman et al., 2011), while exposure during pod initiation and filling causes pod abortion and reduced filling in pods (HanumanthaRao et al., 2016; Tzudir et al., 2014). High temperatures impair canopy development through the reduction of chlorophyll content and stomatal conductance (Chand et al., 2018; Hanif and Wahid, 2018; Patriyawaty et al., 2018; Priya et al., 2019).

In summary flower abscission, earlier and shorter flowering, and impaired canopy development resulting from heat stress could inadvertently leads to poor seed set, reduced number of pods and total seeds per plant, hence low yield in mungbean. Heat stress mitigation in Wyoming's semi-arid climate, characterized by a short growing season and high temperatures, requires the integration of agronomic management and breeding efforts. The identification of early-maturing and heat-tolerant mungbean genotypes is particularly critical for escaping or withstanding periods of heat stress. Agronomic strategies such as supplemental irrigation to optimize soil moisture, residue retention, reduced tillage, adjusted plant density, and intercropping can help lower canopy temperature, reduce evapotranspiration, and sustain physiological processes during heat stress.

In addition, responsive agronomic management and timely irrigation scheduling play an important role in maintaining yield stability under variable heat conditions (De Costa and Shanmugathasan, 1999).

4.2 Implications of cold stress

For mungbean to realize its full production potential as an alternative crop in the semi-arid Mountain West, it is important to investigate the cold tolerance ability of mungbean germplasm for potential winter or cool season cropping. In Wyoming, late planting of essential grain legumes may expose them to frost which might impede their vegetative and reproductive growth stages leading to reduced crop quality, yield and plant death. Cold stress adversely affects chlorophyll synthesis, downregulates genes involved in leaf cuticle formation, and disrupts electron transport and gas exchange, resulting in deleterious effects such as leaf discoloration, flower abscission, and pod deformities (Fridovich, 1986; Allen and Ort, 2001). There have been successes in identifying cold-tolerant lines in other legumes, such as chickpea, at temperatures as low as −8 °C (Wery, 1990; Croser et al., 2003; Mir et al., 2021). Controlled environment studies have demonstrated that both short-term and prolonged mungbean exposure to cold temperatures (around 15 °C) during flowering reduces crop yield (Hu et al., 2022). Also, comparative evidence from other legumes and cereals indicates that cold stress responses may be linked to the regulation of flowering time, with earlier-flowering genotypes potentially escaping frost damage during the reproductive phase (Lejeune-Hénaut et al., 2008; Galiba et al., 2009). However, a significant gap in these findings is the use of very limited genotypes in controlled environments, highlighting the need for comprehensive field-based experimental and extensive screening of broader germplasm, such as AVRDC minicore or USDA mungcore germplasm to discover mungbean genotypes that can withstand cold stress impacts and identify useful alleles to be exploited in the breeding of cold tolerant mungbean varieties adapted to Wyoming's cool season cropping.

4.3 Implications of drought stress

Wyoming is the fifth-driest state in the United States, with nearly 70% of its land area receiving fewer than 16 inches of precipitation annually (Gray and Andersen, 2009). Drought is therefore a persistent and defining feature of the region's climate.

Additionally, ongoing population growth across the state may intensify demand on already limited water resources, including those critical for agricultural production (Gray and Andersen, 2009). Prolonged droughts, especially in rainfed agricultural systems could have detrimental effects on mungbean production. Persistent water deficit in mungbean fields causes chlorophyll depletion and closure of the stomata (Baroowa et al., 2016), thereby limiting photosynthesis and transpiration rates, respectively. Drought stress reduces canopy development and leaf area, resulting in stunted growth through decreased interception of solar radiation and subsequent limitations in photosynthesis and biomass accumulation (Baroowa et al., 2016; El-Nakhlawy et al., 2018). Mungbean yield is significantly impacted by water deficit at both vegetative and anthesis phenological stages. Compared to the highly drought-resilient warm season grasses like sorghum or millet grown in Wyoming, mungbean generally shows moderate drought tolerance and is less adapted to severe or prolonged water deficit. However, when compared to the limited warm season legumes of Wyoming like soybean and dry bean, mungbean is more drought tolerant. To maintain production during prolonged dry conditions of Wyoming's semiarid environment, sorghum and millet have developed physiological and morphological adaptations, such as deeper roots systems, waxier leaf surfaces, and robust stomatal control. In contrast, mungbean because of its short growth cycle and effective water-use systems, performs well under moisture stress but is susceptible during flowering and pod-filling stages, when drought drastically reduces yield. While mungbean has potential as a complementary crop in Wyoming's dryland and irrigated systems, screening diverse mungbean germplasm for identification of tolerant lines with superior root traits that enhance access to deeper soil moisture, along with effective stomatal conductance regulation under water-deficit conditions, could be valuable for breeding programs aimed at developing drought-tolerant varieties suited to Wyoming's cropping systems.

4.4 Implications of biotic stress

Mungbean is susceptible to a wide range of destructive diseases, with disease-related losses representing a major biotic constraint to yield (Iqbal and Mukhtar, 2014). As a crop widely cultivated across Asia, sub-Saharan Africa, and Australia, extensive research has been conducted on the identification, monitoring, and management of viral, bacterial, fungal, and nematode-associated diseases (Batzer et al., 2022a; Batzer et al., 2022b). In contrast, in the United States,

resources such as the *Alternative Field Crop Manual* provide guidance on agronomic practices like seeding, fertility, and harvest but offer limited information on disease identification and control (Oplinger, 1990). Major diseases of economic importance in South and Southeast Asia and Sub-Saharan Africa include Mungbean Yellow Mosaic Disease (MYMD), Cercospora leaf spot (CLS), Powdery mildew, and Anthracnose, with dry root rot emerging as an additional threat (Figure 8) (Nair et al., 2017; Mbeyagala et al., 2017; Pandey et al., 2018).

In the U.S., experimental trials and sentinel plots in Iowa during 2020 and 2021 identified diseases such as Frogeye leaf spot, Rhizoctonia crown rot, and sudden death syndrome (Batzer et al., 2024; Sandhu and Singh, 2020). However, as a relatively new crop in the U.S., mungbean currently lacks well-developed integrated disease management strategies. This is largely due to the limited number of cultivars evaluated and the absence of established commercial production systems (Batzer et al., 2022a; Batzer et al., 2022b). In Wyoming (~42°N latitude), legumes are known hosts of the root-lesion nematode *Meloidogyne hapla* (Griffin and Jensen, 1997), and the most prevalent diseases affecting dry bean production include root rots caused by Rhizoctonia root rot and Fusarium root rot. The use of in-furrow fungicides for managing these diseases in Wyoming has shown

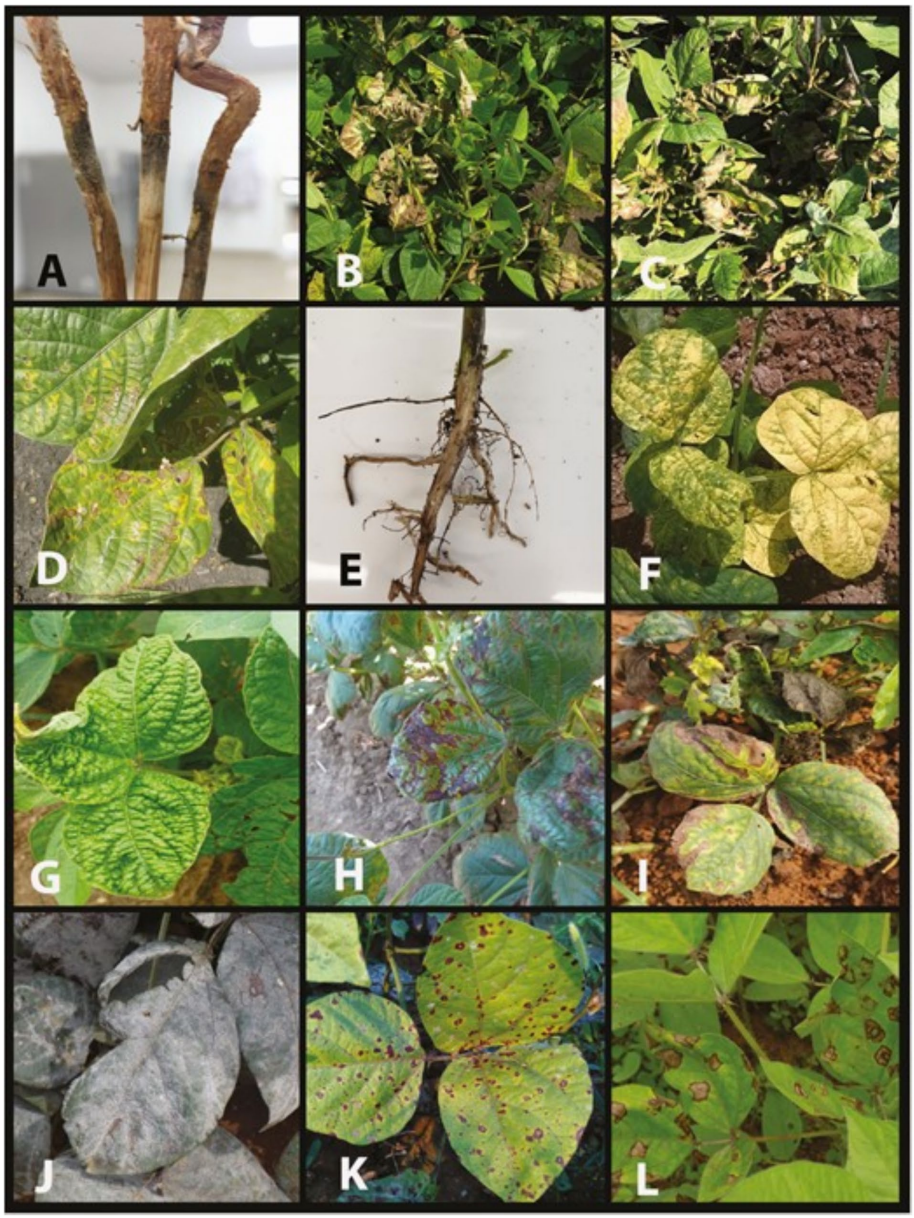


FIGURE 8
Mungbean diseases **(A)** Dry root rot lesions caused by *Macrophomina phaseolina* **(B)** Wet root rot pathogen caused by *Rhizoctonia solani* **(C)** Foliar wilt caused by *Fusarium oxysporum* **(D,E)** Sudden death syndrome caused by *Fusarium virguliforme* on foliage and root **(F)** Yellow mosaic disease (YMD) symptoms **(G)** Stunting, stem thickening, leaf enlargement, and crinkling caused by leaf crinkle virus (LCV) **(H)** Common bacterial blight, characterized by irregular necrotic spots and water soaked haloes that progresses to leaf blight caused by *Xanthomonas axonopodis* **(I)** Tan spot with water-soaked lesions and leaf scorch symptoms caused by *Curtobacterium flaccumfaciens* **(J)** powdery mildew symptoms with white floury appearance on upper leaf surface **(K)** Cercospora leaf spot with irregularly shaped lesions on the leaf surface that gradually become dry and gray **(L)** Anthracnose disease symptoms caused by *Colletotrichum*. Photo credit: (Batzer et al., 2022a; Batzer et al., 2022b).

limited effectiveness, often reducing disease severity without improving yield and, in some cases, causing reduced emergence or temporary phytotoxicity (Stump et al., 2023). Significant variability in susceptibility among pinto bean cultivars suggests a strong genetic component to disease response. Root rot severity is further influenced by environmental conditions, soil compaction, cropping history, and varietal differences, leaving growers with limited management options. Therefore, prior to widespread mungbean adoption in Wyoming, it will be essential for extension and agronomic programs to develop region-specific disease management recommendations, drawing on knowledge from other legumes while advancing germplasm screening for resistance to root rot pathogens, other diseases, and evaluating effective chemical and integrated control strategies.

5 Conclusion

Introduction of mungbean into the Wyoming agricultural economy could benefit the diversification of its dryland cropping system as a good alternative for a warm season legume in dryland farming and could help meet the long demand for a well-adapted warm season legume for use in cover crop mixes in Wyoming and Montana. It also has potential to complement the current rotation system as an intercrop or rotation crop. Wyoming farmers could also benefit from additional income from sale of mungbean grains because of the recent increase in demand of mungbean in North America (Quazaz et al., 2019; Hirtzer et al., 2021; King, 2020) due to renewed interest for protein-based diets from mungbean, pea (*Pisum sativum* L.), and soybean (*Glycine max* (L.) Merr.), which exceeded $1 billion in sales during 2020 (Robinson and Mulvany, 2020). With importation of nearly all mungbean consumed in the U.S., this crop has tremendous potential as a domestic crop and alternative cash crop (Batzer et al., 2022a; Batzer et al., 2022b). However, several significant limitations must be considered, including agronomic uncertainties pertaining to varietal adaptation, yield stability, and water-use efficiency under Mountain West semi-arid conditions, as well as climatic constraints like Wyoming's short growing season, temperature variability, and risk of early frost. Inadequate processing and marketing facilities, a lack of established supply chains, and farmers' lack of knowledge with mungbean can all be obstacles to adoption.

The long-established varieties (Berken, Satin, and OK12), which were developed over 50 years ago, remain the only improved mungbean cultivars widely available to U.S. farmers and may not be well adapted to the environmental conditions of the Mountain West region. More recently, pre-breeding trials of hundreds of experimental lines have been performed at Texas A&M University and Oklahoma State University. Tennessee State University and Iowa State University are currently evaluating mungbean germplasm for the potential to use in the development of new cultivars (Sandhu and Singh, 2020). It is time for the West, particularly research institutions in the Mountain States region to key into this next-generation cash crop which could boost its agricultural economy.

Future research should prioritize the development of early-flowering, stress-tolerant genotypes, alongside the optimization of agronomic practices tailored to local environmental conditions. The establishment of regional value chains, coupled with targeted extension initiatives, will be essential to promote producer adoption and ensure long-term integration into existing cropping systems.

Experimental trials should be expanded to evaluate a larger number of genotypes across diverse environments, using high-throughput phenotyping tools that enable more accurate measurement of key indices and correlated traits. Furthermore, genomics-assisted breeding approaches are needed to better understand the genetic basis of traits associated with adaptation to abiotic stresses. Such insights will support genomic selection and the stacking of multiple genes with desirable traits into improved cultivars, thereby accelerating genetic gain for abiotic stress.

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