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Forage Soybean: Unveiling Its Potential in the Wheat-Based Rainfed Cropping Systems

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Abstract: The Midwestern region of the United States has been experiencing periodic forage shortages due to frequent droughts, a growing livestock population, and reliance on traditional farming practices. This study evaluated the dry matter yield (DMY), forage nutritive value, water use efficiency (WUE), and economic viability of forage soybean [*Glycine max* (L.) Merr.] in a no-till winter wheat-based rainfed cropping system in the Midwest, USA. The research aimed to identify alternative summer forage crops that are drought-resilient, require lower inputs, mitigate seasonal gaps, and provide higher DMY and forage nutritive value compared to traditional forages. A four-year field experiment in a randomized complete block design with four replications assessed these parameters at various growth stages and planting dates. Results showed that forage soybean had a high DMY (12.1 Mg ha^{-1}), especially when optimally planted and harvested at the R3 stage. Forage nutritive value, including crude protein (CP), in vitro dry matter digestibility (IVDMD), and relative feed value (RFV), was highest at early vegetative stages (V2-V3), meeting livestock nutritional requirements. Forage soybean also demonstrated good WUE (21 kg ha^{-1} mm^{-1}), making it suitable for water-limited regions. Economic analysis indicated substantial net profits ($322 per hectare), confirming its economic viability. The study concludes that forage soybean is a promising summer forage option for Midwest growers, offering high-quality forage, efficient water use, and economic benefits. Further research, particularly animal feeding trials, is recommended to validate its potential for widespread adoption in cropping systems.

Keywords: forage soybean; rainfed cropping systems; dry matter yield; forage nutritive value; water use efficiency; economic viability

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1. Introduction

A continuous dryland winter wheat (*Triticum aestivum* L.) based cropping system is prevalent in the Midwest region of the United States, particularly in the Central Great Plains [1–4]. Traditionally, these systems involve a two-year rotation of wheat and fallow or a three-year rotation of wheat, grain sorghum (*Sorghum bicolor* L.), or maize (*Zea mays* L.), and fallow [5,6]. Farmers typically grow grain sorghum (milo), soybean, or maize after the wheat harvest. Rainfed farming, which relies on natural rainfall rather than extensive irrigation, is commonly practiced in this region. However, this dependence on rainfall presents significant challenges, as drought conditions frequently limit crop production [7–10]. Therefore, rainfall distribution, soil type, and individual farm management practices primarily influence crop rotation decisions.

The demand for forage in this region is growing as the livestock population increases each year [11]. The livestock industry is crucial to the economy of the Midwest region, with Texas, Missouri,

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Oklahoma, and Kansas ranking first, third, fifth, and seventh, respectively, in national cattle and calf production in 2023 [12–14]. Thus, forage production is essential to support the expanding livestock industry in this region. Major forage crops grown in the Midwest region include alfalfa (*Medicago sativa* L.), tall fescue (*Schedonorus arundinaceus* L.), bermudagrass (*Cynodon dactylon*), switchgrass (*Panicum virgatum* L.), sorghum-sudangrass (*Sorghum bicolor x Sorghum sudanese*) and maize silage.

Numerous challenges persist despite the increasing demand and economic importance of forage production. Seasonal forage shortages are common due to traditional winter wheat-based practices, competition with other cash crops, the expansion of the feed and ethanol industries, rising fertilizer prices [15], and unpredictable weather events such as drought, hail, and extreme cold and wet winters [16]. These factors significantly affect forage production, area, forage yield and forage nutritive value (FNV), leading to an increase in the cost of livestock production.

Projections indicate that the Midwest will experience higher average temperatures and more unpredictable rainfall patterns in the future [17]. This variability could further disrupt livestock production by impacting forage supply. Therefore, exploring alternative forage crops that are resilient to drought and have greater water efficiency is crucial for ensuring a reliable feed source during dry summers.

Furthermore, the livestock farmers in this region often encounter a summer shortage of high-quality forages [18]. While winter wheat serves as a dual-purpose crop and provides grazing for cattle during late fall and early spring, there is a shortage of high-quality forages from late July through November. In this situation, farmers should consider exploring alternative annual forages after harvesting wheat. Hence, this study also aimed to mitigate seasonal gaps in forage availability, particularly in addressing shortages during summer months, thereby providing a consistent supply of high-quality forage throughout the year.

Exploring alternative forages that promote soil health and erosion control is another key consideration because some forage legumes can enhance microbial activities and fix atmospheric nitrogen to the soil as well as reduce soil erosion. The motivation for this study is further driven by market opportunities. Reduced input costs, achieved through alternative forage crops that demand fewer production inputs like water and fertilizers, and higher biomass yield lead to an increase in net farm income and promote sustainability and cost-effectiveness for farmers.

FNV analysis is another component of this study because high-quality forage improves animal performances such as body weight gain, reproduction, and milk production. Different animal types have different nutritional requirements. For example, the optimum relative forage quality (RFQ) required for milking cows is 150, while growing heifers, beef, and other animals require a lower value [19]. Likewise, the nutritive value varies depending on the type of forage, planting time and its stage of maturity [20]. For instance, alfalfa has a high nutritive value as forage compared to other forage crops [21]. Hence, it is important to understand the nutritive value parameter of potential forage crops for decision making. Furthermore, providing a variety of forage crops in animal diets helps improve their health by offering different nutrients. Additionally, the hay market price is determined by the FNV parameter. The RFQ above 140 is considered as premium quality hay and normally has higher market value whereas RFQ below 90 is considered as utility and has the lowest market value [22].

Several prior studies have established that forage soybean [*Glycine max* (L.) Merr] is a high-yielding, drought-tolerant crop with high protein content, weed-suppressing abilities, and an extended growing season. Previous research reported forage dry matter yields (DMY) exceeding 8 Mg ha^{-1} when harvested at early flowering (R1) to the pod formation stage (R3-R7) [3,20,23,24]. Forage soybean, as a legume, also supplies nitrogen to the soil through nitrogen fixation. However, its adoption as a summer forage in the Midwest has been limited, and there is insufficient research on its potential benefits in the United States.

This study aims to explore alternative summer forage crops that are drought-resilient, mitigate seasonal forage gaps, require lower production inputs, offer higher yields, possess better nutritional quality, and enhance profitability. The primary objective is to evaluate the DMY, FNV, water use efficiency (WUE), and profitability of forage soybean grown under rainfed conditions. The ultimate goal is to identify alternative crops suitable for winter wheat-based cropping systems in the Midwest region of the United States.

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2. Materials and Methods

2.1. Study Location

A four-year field experiment (October 2019-October 2023) was conducted at the Ashland Bottoms Experiment Research Station in Manhattan, Kansas, USA (39.124945°N latitude, -96.635112°W longitude). The soil at the site is classified as silty clay loam with a 0 to 1% slope. Key soil properties include a pH of 6.4, total nitrogen of 0.13%, organic carbon of 1.38%, Mehlich extractable phosphorus of 20.44 μg g^{-1}, potassium of 323 μg g^{-1}, bulk density of 1 g cm^{-3}, and volumetric water content of 33% at a depth of 0 to 20 cm. The previous cropping system was a sorghum-soybean-wheat conventional tillage rotation.

2.2. Climatic Conditions

The 30-year average summer crop growing season (March-October) rainfall is 710 mm, with monthly averages ranging from 46 mm in March to 123 mm in June. Average temperatures during this period range from 7°C in March to 27°C in July. Spring temperatures increase from an average maximum of 14°C in March to 25°C in May. Summer is characterized by warm to hot temperatures, with maximums from 30°C in June to 33°C in July. Autumn temperatures drop from an average maximum of 27°C in September to 13°C in November. Winters are cold, with temperatures often dropping below freezing, and an average maximum range from 6°C in December to 8°C in February. The average frost-free period is approximately 179 days [25].

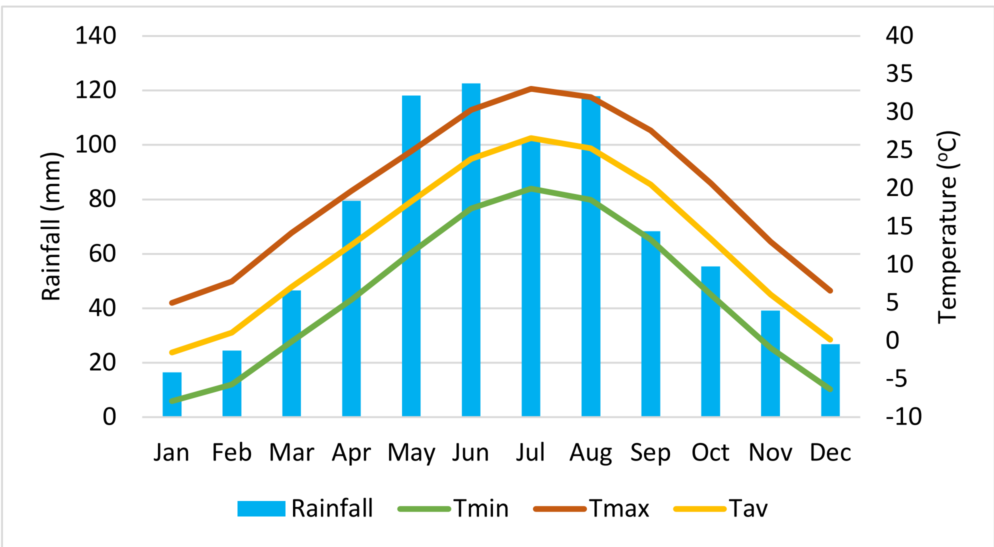

Figure 1. Average monthly rainfall and temperature normals (1991-2020) of Manhattan, Kansas. This includes minimum temperature (Tmin), maximum temperature (Tmax), and average temperature (Tav) [26].

2.3. Experimental Design

The experiment was designed as a randomized complete block with four replications. Each plot measured 12.19 meters wide and 15.24 meters long. Seven treatment combinations were tested, varying in cropping sequence, cropping intensity, and diversity. The sequences included a three-year crop rotation of winter wheat-forage soybean-winter wheat and a four-year rotation of winter wheat-fallow-winter wheat-forage soybean.

2.4. Crop Establishment

Winter wheat and forage soybean were planted at either optimal or late dates from 2019 to 2023, particularly in double cropping scenarios. Optimal planting dates for winter wheat were mid to late October (15 Oct-22 Nov), while forage soybean was sown in mid-May (17-22 May). Late planting dates for winter wheat were early to mid-November (07-22 Nov), and forage soybean was sown in early July (06-08 July). Wheat was planted with a 19 cm row spacing using a 9-row Great Plains 506® no-till drill. Forage soybean var. Large Lad RR™ was planted at a 1.2 cm depth with a 76 cm row

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spacing, following winter wheat harvest, using zero tillage. No chemical fertilizers were applied for summer legumes.

2.5. Forage Dry Matter Yield (DMY)

Samples were collected from a 0.14 m^2 area within each plot at the vegetative stages (second and third trifoliate leaves, V2 and V3) and reproductive stages (beginning of flowering, R1, and beginning of pod formation, R3). Plants were harvested 2-5 cm above ground level using a hand sickle and dried at 60°C for 72 hours. Dried samples were weighed, and values from each 0.14 m^2 sample were converted to DMY in Megagrams per hectare (Mg ha^{-1}).

2.6. Forage Nutritive Value (FNV)

Dried samples were finely ground (< 1 mm) using a Wiley mill (Wiley® Mill 4 1/2 HP, Thomas Scientific, NJ, USA). Key forage nutritive value parameters including crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), in-vitro dry matter digestibility (IVDMD), relative feed value (RFV), and relative forage quality (RFQ) were analyzed using near-infrared reflectance spectroscopy (NIRS), as described by Marten *et al.* [27].

2.7. Statistical Analysis

The analysis of variance (ANOVA) for DMY and FNV was conducted using PROC GLIMMIX in SAS 9.4 [28]. Planting date and growth stage were treated as fixed effects, while production year and replications were considered random effects. Pairwise comparisons of least square means for DMY and FNV were performed using the Tukey-Kramer method with the LSMEAN function in SAS 9.4. All figures were generated using the TIDYVERSE package in R 4.3.0[29]. Model assumptions were verified by examining residuals and quantile-quantile plots.

2.8. Water Use Efficiency (WUE)

WUE was calculated as the ratio of DMY to crop evapotranspiration (ETc). ETc was determined using the crop coefficient (Kc) method from FAO Irrigation and Drainage Paper No. 56 [30]. The Kc method is a widely recognized approach for estimating evapotranspiration (ET) in agricultural systems [31]. Daily ETc was computed as the product of daily reference evapotranspiration (ETo) from Kansas Mesonet, located 150 meters from the field, and the Kc values for wheat and soybean at different growth stages. The equations for ETc and WUE are as follows:

$$ET_c = ETo \times K_c \quad (1)$$

where:

ET_c = Actual crop evapotranspiration from planting to forage biomass harvesting time

ET_o = sum of daily reference evapotranspiration from planting to forage biomass harvesting time obtained from Kansas Mesonet

K_c = Crop coefficient of forage soybean at specific growth stage

$$WUE = DMY/ET_c \quad (2)$$

Where:

DMY = forage dry matter yield of particular crop expressed in Kg

WUE = Water use efficiency, the ratio of the forage DMY produced to the amount of water transpired by forage soybean from planting to harvesting period, expressed in kg ha^{-1} mm^{-1}.

2.9. Cost-Benefit Analysis

Cost-benefit analysis was computed using observed DMY harvested at the R1 growth stage for forage soybean, with a 20% deduction for assumed harvesting and storage loss [32–34]. Seed and chemical input costs were based on K-State Research and Extension recommendations [35,36] and the current market value. Variable costs such as seed, planting, harvesting, and baling costs were based on Kansas Custom Rates 2022 [37]. Land rental rates were determined using the Kansas 2022 Farm Real Estate Value and Cash Rent [38]. The analysis included the entire haying operation, with hay prices determined by the Kansas Direct Hay Report [39]. A 5% overhead cost and a 6% interest rate were incorporated into the overall expenses. The Kansas sales tax rate of 6.5% was added to the total sales income to get net farm income. The net farm income was calculated by subtracting total costs from total revenues.

3. Results

3.1. Forage Dry Matter Yield

Dry matter yield varied significantly with growth stage and planting date. The highest DMY was observed at R3 growth stage during optimum planting (12.1 ± 0.9 Mg ha^{-1}), followed by R1 stage (9.5 ± 1.8 Mg ha^{-1}) and V3 stage (4.3 ± 0.9 Mg ha^{-1}). The lowest yield was recorded at V2 stage (3.3 ± 0.7 Mg ha^{-1}). For late planting, the highest DMY was noted at R3 stage (8.5 ± 3.1 Mg ha^{-1}), with the lowest yield at V2 stage (2.9 ± 0.8 Mg ha^{-1}).

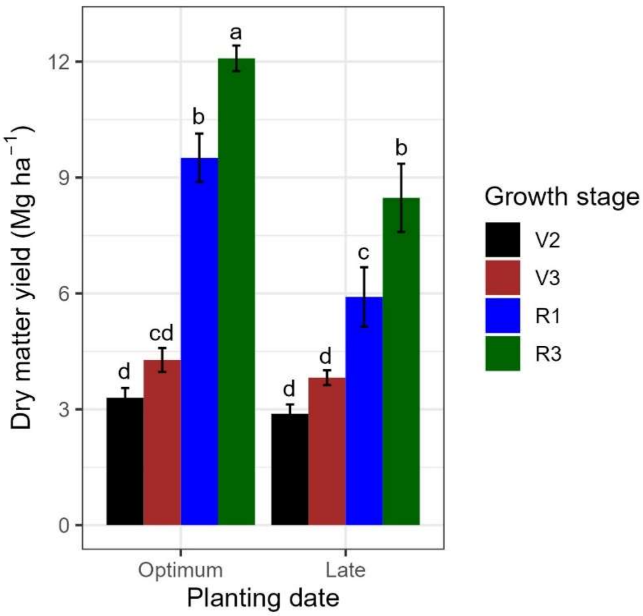

Figure 2. Forage dry matter yield of optimum and late planted forage soybean harvested at different growth stages. In the legends, V2 is the vegetative stage with second trifoliate leaf, V3 is the vegetative stage with third trifoliate leaf, R1 is the reproductive stage at the beginning of flower and R3 is the reproductive stage at the beginning of pod formation.

3.2. Forage Nutritive Value

There was no significant difference in overall forage quality between the two planting dates; however, the forage biomass harvested at early vegetative growth stages (V2-V3) showed higher forage quality (Table 1.).

Table 1. Forage nutritive value analysis of forage soybean based on planting date and growth stage.

Planting date	Growth stage	CP	ADF	NDF	Lignin	TDN	NDFD	IVDMD	RFV	RFQ
		-- % ------------------ ---------								
Optimum	V2	22.2 a	32.6 cd	35.5 cd	6.8 cd	57.9 bc	55.0 a	81.4 bc	169.0 bc	201.6 bc
	V3	20.0 a	35.1 abcd	38.2 bc	7.3 abcd	56.0 bc	51.0 ab	79.2 c	152.6 bcd	177.6 bcd
	R1	14.1 bc	39.8 a	46.5 a	8.5 ab	52.8 c	42.0 c	72.4 d	119.3 d	126.6 ef

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	R3	12.9 c	39.5 ab	46.9 a	8.6 a	54.3 c	40.8 c	72.1 d	118.4 d	125.1 f
Late	V2	21.8 a	24.8 e	28.1 d	5.0 e	63.7 a	56.0 a	88.0 a	232.8 a	271.4 a
	V3	20.5 a	29.1 de	32.9 cd	5.9 de	60.5 ab	52.2 ab	84.7 ab	190.1 b	218.4 b
	R1	16.6 b	33.3 bcd	38.7 bc	7.2 bcd	57.4 bc	47.7 bc	79.8 bc	154.2 bcd	171.6 cde
	R3	15.2 bc	37.3 abc	43.4 ab	7.8 abc	54.4 c	45.9 bc	76.8 cd	130.5 cd	143.9 def
Interaction		ns	ns	ns	ns	ns	ns	ns	ns	ns

Different letters within the same column indicate significant differences at $p < 0.05$.

CP content showed significant differences based on growth stages and planting dates. The highest CP content was recorded at V2 stage for both optimum (22.2%) and late planting (22.0%), while the lowest CP content was at R3 stage for both planting dates (12.9% for optimum and 16.8% for late planting). AD) and NDF content also varied significantly. For optimum planting, ADF content ranged from 32.6% at V2 stage to 39.8% at R1 stage. NDF content was highest at R1 stage (46.5%) and lowest at V2 stage (35.5%). In late planting, ADF content was lowest at the V2 stage (25.6%) and highest at R3 stage (33.7%). NDF content followed a similar pattern, with the lowest at V2 stage (28.8%) and highest at R3 stage (39.2%). TDN were highest at V2 stage for late planting (63.1%) and lowest at R1 stage for optimum planting (52.8%). Lignin content was lowest at V2 stage for late planting (5.1%) and highest at R3 stage for optimum planting (8.6%). IVTDMD was highest at V2 stage for late planting (86.8%) and lowest at R3 stage for optimum planting (72.1%). RFV and RFQ values were highest at V2 stage for late planting (225.5 and 262.4, respectively) and lowest at R3 stage for optimum planting (118.4 and 125.1, respectively).

3.3. Water Use Efficiency

Cowpea demonstrated the highest WUE (26.8 kg ha^{-1} mm^{-1}) among the legumes evaluated. In comparison, soybean and forage soybean exhibited moderate efficiencies of 22.1 kg ha^{-1} mm^{-1} and 21.3 kg ha^{-1} mm^{-1}, respectively, indicating their relatively good performance in utilizing water effectively. Alfalfa followed closely with a WUE of 18.8 kg ha^{-1} mm^{-1}, a slightly lower efficiency than the soybeans. Moth and tepary beans, on the other hand, showed comparatively lower WUE values, below 15 kg ha^{-1} mm^{-1}.

3.4. Cost Benefit Analysis

The cost-benefit analysis of various summer legumes grown in the study period was calculated to determine their economic viability. The results, summarized in Table 2, showed significant differences in costs, revenues, and net profits among the crops evaluated.

Table 2. Cost-benefit analysis of summer legumes grown in Kansas ($ per hectare).

Financial parameters	Soybean	Forage soybean	Cowpea	Tepary	Moth	Alfalfa
Variable cost	420.05	613.09	510.86	367.99	410.02	1219.36
Fixed cost	226.4	226.4	226.4	226.4	226.4	226.4
Total production cost	646.45	839.49	737.26	594.39	636.42	1445.76
Revenue	642.47	1161.39	741.32	321.24	444.79	2322.79

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Net profit	-3.98	321.90	4.05	-273.15	-191.63	877.03

The variable costs varied significantly among the crops, with alfalfa having the highest variable cost at $1,219.36 per hectare, followed by forage soybean at $613.09 per hectare. Cowpea, moth, and soybean had moderate variable costs of $510.86, $410.02, and $420.05 per hectare, respectively. Tepary had the lowest variable cost at $367.99 per hectare. Fixed costs were consistent across all crops at $226.40 per hectare. The total production cost, combining variable and fixed costs, was highest for alfalfa at $1,445.76 per hectare followed by forage soybean with the production cost of $839.49 per hectare. Cowpea, soybean, and moth had similar production costs of $737.26, $646.45, and $636.42 per hectare, respectively. Tepary had the lowest total production cost at $594.39 per hectare. Net profit per hectare was calculated to assess the overall financial performance of each crop. Alfalfa yielded the highest net profit at $877.03 per hectare. Forage soybean also showed significant profitability with a net profit of $321.90 per hectare. Cowpea generated a small net profit of $4.05 per hectare. In contrast, soybean, tepary, and moth incurred net losses. Soybean had a minor net loss of $3.98 per hectare, while moth and tepary faced substantial net losses of $191.63 and $273.15 per hectare, respectively.

4. Discussion

This study investigated the dry matter yield, forage nutritive value, water use efficiency, and economic viability of forage soybean grown under a no-till winter wheat-based rainfed cropping system.

4.1. Dry Matter Yield

DMY increased significantly with advancing growth stages for both planting dates, reflecting progressive biomass accumulation (Figure 1). Optimum planting resulted in consistently higher DMY (up to 30%) compared to late planting, emphasizing the importance of timely establishment and optimal harvesting stages for achieving higher forage yields. Forage soybean, although less commonly grown for forage purposes in the Midwest region of the United States, demonstrated the highest potential for DMY when planted and harvested at optimal times. This aligns with previous research indicating that yield potential is maximized under optimum planting times, as delayed planting negatively affects soybean vegetative growth and yield [40–42].

4.2. Forage Nutritive Value

Forage quality generally diminishes as it matures [20,43]. In this study, higher forage nutritive value, including CP, IVDMD, and RFV, was observed in the early vegetative stages (V2-V3) compared to the reproductive stages (R1-R3) (Table 1). These findings indicate a trade-off between yield and quality, with earlier harvests providing high-quality forage while later harvests maximize total biomass production. According to USDA hay quality guidelines, good quality hay should have a CP content greater than 18%, ADF below 32% and RFV above 150 [39]. Additionally, different types of animals have specific forage quality preferences. For example, the forage with RFV above 140 is highly recommended for dairy cows in their first trimester of pregnancy and dairy calves whereas the recommended RFV for heifers aged 12-18 months and lactating beef cows is between 115 to 130 [19]. The results of the nutritive value analysis indicated that forage soybean met the criteria for good quality hay when harvested during vegetative growth stages (Table 1), fulfilling the nutritional requirements for all types and classes of animals, regardless of planting time differences.

4.3. Water Use Efficiency

Forage soybean demonstrated good WUE compared to soybean and alfalfa, indicating its suitability for regions with water limitations (Figure 3). Additionally, cowpea emerged as the most water-use efficient legume in this study, suggesting a potential alternative in areas with severe water scarcity. Our estimated WUE aligns with previous findings reported by Nielsen [3], who estimated WUE of forage soybean grown under similar production environment and management practices- a no-till wheat-based rainfed cropping system in the study region.

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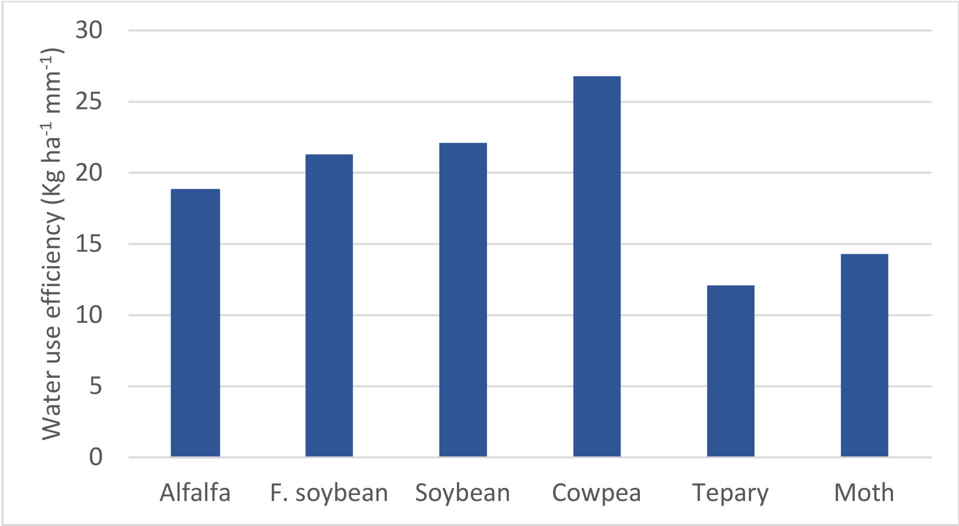

Figure 3. Water use efficiency (WUE) of alfalfa harvested at late bud stage, and soybean, forage soybean, cowpea, moth and tepary bean harvested at early reproductive (R1) growth stage.

4.4. Economic Viability

The cost-benefit analysis indicated that forage soybean is an economically viable crop with substantial net profits under the rainfed production system (Table 2). Although it does not generate the highest net income compared to alfalfa, forage soybean requires significantly less water [21] and has much lower production costs, making it a more accessible option for many farms. These economic advantages suggest that forage soybean could enhance farm profitability while ensuring sustainability in rainfed cropping systems.

4.5. Practical Implications

The study findings strongly suggest that forage soybean has the potential to be a promising summer forage option for growers in the Midwest region. Its ability to produce high yields, meet nutritional requirements, and efficiently use water makes it a valuable addition to crop rotations in regions where dryland winter wheat-based rainfed cropping system is prevalent. However, further research is needed to explore its full potential and address any agronomic challenges.

4.6. Future Research Directions

Future research should focus on animal feeding trials to assess palatability, digestibility, and animal performance on forage soybean diets. Such studies would provide more compelling evidence for the integration of forage soybean into Midwestern cropping systems. Additionally, exploring the long-term impacts of forage soybean on soil health and subsequent crop yields would be beneficial for sustainable agricultural practices.

5. Conclusions

This study found several key strengths of forage soybean, making it a promising summer forage option for farmers in the Midwest region of the United States. Notably, forage soybean demonstrated the ability to produce high dry matter yield under rainfed conditions, while meeting the criteria for good quality hay. It exhibited commendable water use efficiency compared to alfalfa and soybean, making it well-suited for drought-prone areas. Furthermore, high-quality forage with good CP, IVDMD and RFV found in forage soybean during its vegetative growth stages meets the nutritional requirements for various types of livestock. This makes forage soybean a valuable addition to crop rotations in regions predominantly practicing winter wheat-based rainfed cropping systems.

Cost-benefit analysis indicated that forage soybean is an economically viable crop. Despite not generating the highest net income compared to alfalfa, forage soybean requires significantly less water and has much lower production costs, making it an accessible and sustainable option for many farms. The cost-benefit analysis showed that forage soybean had substantial net profits under the rainfed production system, underscoring its potential for enhancing farm profitability.

Our findings revealed that forage soybean is a valuable summer annual forage option for producers after harvesting winter wheat for the producers of the Midwest, particularly due to its high DMY, nutritious forage, water-efficient growth, and economic viability. However, further research is warranted to solidify its potential for widespread adoption.

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Conflicts of Interest: The authors declare no conflicts of interest.

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