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PERFORMANCE AND PROSPECTS OF MILLET-BASED CROP ROTATIONS: YIELD, ENERGY, AND ECONOMIC INSIGHTS IN SEMI-ARID ZONE OF HISAR

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ABSTRACT
A field experiment was conducted at CCSHAU, Hisar during Kharif seasons of 2022–23 and 2023–24 in randomized block design in both Kharif and Rabi seasons, replicated thrice with eight treatments (foxtail millet, little millet, browntop millet, proso millet, kodo millet, barnyard millet, finger millet, and pearl millet) in the Kharif season and each millet was rotated with three major rabi crops i.e. wheat, raya and chickpea. Thus, a total of 24 crop rotations with three replications during the rabi season. Results revealed that the pearl millet–Indian mustard closely followed by foxtail millet–Indian mustard was found most economical and energy efficient with 4.8 and 30.4% higher net returns, 8.5 and 5.8% higher B:C ratio, 12.9 and 43.2% higher returns/day, 6.9 and 58.2% higher output energy, 10.8 and 61.3 percent higher net energy returns than pearl millet–wheat and pearl millet–chickpea crop rotations, respectively. Among all millet-based crop rotations, pearl millet followed by wheat/Indian mustard/chickpea rotations were recorded with significantly higher net returns (71.5/75.0 /57.5 × 103 ₹/ha), B:C ratio (1.52/1.65/1.56) and per day returns (311/351/245 ₹/day/ha), output energy (303.3/324.4/205 × 103 MJ/ha) and net energy returns (274.6/304.5/188.7 × 103 MJ/ha), respectively. Little millet/finger millet-Indian mustard/chickpea rotations proved most uneconomical. Pearl millet/ Foxtail millet-based crop rotations with Indian mustard can make their crop rotations economically profitable and energy efficient.

KEYWORDS: Crop rotation, Millets, Net returns, B:C ratio and Net energy returns

INTRODUCTION
Haryana, occupying just 1.4% (4.4 million hectares) of India's total geographical area, ranks as the second-largest contributor to the central food grain pool (14%) after Punjab. With approximately 70% of its population engaged in agriculture, the state has made remarkable strides in the sector. Since 1966–67, Haryana has increased its food grain production from 2.6 million tonnes to 17.4 million tonnes in 2023–24, an impressive eleven-fold rise in wheat and a sixteen-fold increase in rice production during this period (Department of Agriculture and Farmers', 2024). Despite these achievements, the state's agricultural sector now faces pressing challenges: enhancing crop productivity, profitability, and resilience amidst a growing population, depleting natural resources, intensifying climate change, and declining farm incomes (Pathak et al., 2022).

Cereal crops form the foundation of India's food security, particularly for its predominantly vegetarian population, as they serve as primary sources of carbohydrates, proteins, and other essential nutrients (Singh et al., 2025). Consequently, cereal-based production systems continue to dominate the agricultural landscape, contributing substantially to national food supply and caloric intake. In Haryana, the major cropping systems include Rice–Wheat, Cotton–Wheat, and Pearl millet–Mustard rotations. Among these, the Rice–Wheat system is the most widely adopted, followed by Cotton–Wheat in certain agro-climatic zones. The Pearl millet–Mustard system is typically practiced in the drier, semi-arid regions of the state. However, these traditional systems are increasingly facing constraints such as groundwater depletion, declining soil fertility, and stagnating yields (Patel et al., 2023; Sammauria et al., 2020). Therefore, there is a critical need for diversification strategies to reduce the risks associated with overdependence on the Rice–Wheat system and to enhance long-term sustainability (Dhaka et al., 2024). The continuous adoption of the Rice–Wheat cropping system in the fertile and well-irrigated regions of Haryana has led to a rapid depletion of the natural resource base and deterioration of soil health. This has manifested in various forms of land degradation, including soil compaction, salinity, sodicity, waterlogging and accumulation of pesticide residues. Additionally, there has been a significant decline in soil organic carbon and a disruption of the region's hydrological balance, ultimately contributing to a sharp increase in the cost of cultivation (Dhaka et al., 2025). These ecological concerns have also intensified pollution levels across soil, water, and the broader environment within the state. In light of these challenges, farm diversification emerges as a viable and strategic approach to sustaining agricultural productivity and ecological integrity in Haryana (Haryana Kisan Ayog Report, 2014).

Crop diversification, defined as the introduction or incorporation of alternative crops into existing farming systems, can be implemented at both individual farm and regional levels. It represents one of the most ecologically sustainable, economically viable, and risk-mitigating strategies, particularly for smallholder farmers operating under uncertain climatic and market conditions (Kumar et al., 2023; Yadav et al., 2017).

The pearl millet-wheat cropping system is the second most important cereal-based system after the rice-wheat system in the Indo-Gangetic Plain (IGP) of India, covering an estimated 2.26 million hectares. It is also one of the dominant crop rotations in the sandy loam region of Southern Haryana, India. Other common cropping systems practiced in Haryana are rice-wheat, cotton-wheat, pearl millet-mustard, and pearl millet-chickpea cropping systems (Dhaka et al, 2024a; Kumar et al., 2022; Ramadas et al., 2019). Incorporating minor millets (finger millet, foxtail millet, proso millet, little millet, browntop millet, kodo millet and barnyard millet) in addition to pearl millet into existing crop rotations offers a promising avenue for diversifying crop rotations in Haryana, particularly in the regions facing water scarcity and soil degradation persist (Singh et al., 2023; Hemalatha et al., 2021; Bandyopadhyay et al., 2017; Habiyaremye et al., 2017). Millets are well-suited to diversify pearl millet-wheat, pearl millet-chickpea, and pearl millet-raya cropping systems to improve soil health, water use efficiency, and overall sustainability.

India contributes about 20% and 80% of total millet production in the world and Asia, respectively. Thus, among the major millets, India ranks first in the world in pearl millet and third in sorghum cultivation (Dhaka et al., 2023). In India, millets are cultivated over an area of 12.45 million hectares, producing 15.53 million tonnes with an average yield of 1247 kg/ha (ASSOCHAM, 2022). There is an immediate need to promote the cultivation of millets to ensure food and nutritional security at the national level because small millets are considered climate-smart and nature-friendly crops (Jeeva et al., 2024; Dhaka et al., 2023a). Thus, millets can play a vital role in the livelihoods of the poor and malnourished population, provide food and nutrition security, and help achieve the first three Sustainable Development Goals (SDGs) of the United Nations: reducing poverty, zero hunger, good health and well-being. Farmers need to be continuously motivated and encouraged to pursue crop diversification for better sustainability, as well as income and employment opportunities (Sammauria et al., 2020). However, very limited research work has been conducted so far on different minor millets, except pearl millet-based crop rotations in Haryana. Therefore, keeping all these points in view, a field experiment was conducted at CCS Haryana Agricultural University, Hisar, Haryana, India, to study the yield, economic, and energy performance of eight different millet-based crop rotations with the major Rabi crops of Haryana.

MATERIALS AND METHODS

A field experiment was conducted at the Agronomy field research area of CCS Haryana Agricultural University, Hisar, Haryana, India (29°10’N latitude, 75°46’E longitude, and 215.2 M altitude) during 2022–23 and 2023–24 in a randomized block design in both kharif and rabi seasons, replicated thrice with eight treatments (foxtail millet, little millet, browntop millet, proso millet, kodo millet, barnyard millet, finger millet, and pearl millet) in the Kharif season and each millet was rotated with three major rabi crops i.e. wheat, raya and chickpea. Thus, a total of 24 crop rotations with three replications during the Rabi season were studied to evaluate yield, energy, and economic performance. The soil of the field was sandy loam in texture, slightly alkaline in pH (7.6), low in organic carbon (0.15%), poor in available phosphorus (7.37 kg/ha), medium in available nitrogen (157.2 kg/ha), and rich in available potassium (231.7 kg/ha). The maximum and minimum temperatures during the crop study period were conducive to the growth and development of crops. Sowing of all millets, namely, foxtail millet (SIA 3156), little millet ‘DHLM 36-3’, browntop millet ‘IIMR AK 2’, proso millet (TNAU 202), kodo millet ‘JK 41’, barnyard millet ‘VC 27’, finger millet ‘GPU 67’, and pearl millet ‘HHB 67’, in the Kharif season was done on 27th July 2022, 19th July 2023 and these were harvested at 78, 92, 73, 69, 91, 78, 116, and 71 days after sowing, respectively. Agronomic management for each millet was carried out separately as per the recommendations of the Indian Institute of Millets Research, Hyderabad. During the Rabi season, all millets were followed by wheat ‘WH 1105’, raya ‘RH 725’ and chickpea ‘HC 7’. The sowing of wheat and raya/chickpea was done on 27th October (but 29th November after finger millet) and 20-27 October (but 29th November after finger millet), respectively during 2022, while during 2023 sowing of wheat and raya/chickpea was done on 1st November (but 3rd December after finger millet) and 21–29 October (but 2nd December after finger millet), respectively after all millets. The harvesting of wheat, raya and chickpea took 230–256, 211–242 and 232–250 days, respectively, after sowing. Maximum days to harvesting of rabi crops were observed after foxtail millet and little millet. The climate for millets during kharif 2022 was unfavorable due to excessive rainfall compared to kharif 2023. Similarly, the rabi season 2023–24 was more favorable to wheat, raya and chickpea due to more rainfall compared to the rabi 2022–23 season. As per the meteorological data provided by Department of Agro meteorology, CCS Haryana Agricultural University, Hisar, the mean maximum temperature, minimum temperature, relative humidity, wind speed, bright sun shine hours, PAN evaporation, total rainfall, total rainy days during Kharif 2022 (July- October) and Kharif 2023 (July–October) were 33.6oC, 24.5oC,61.9–88.0 %, 5.0 km/hr, 6.3 hr/day, 4.0 mm/day, 549.4 mm, 17.0 days and 35.0oC, 24.1oC, 54.0–85.4%, 5.3 km/hr, 6.6 hr/day, 4.8 mm/day, 457.3 mm, 11.0 days, respectively. Similarly, during rabi 2022–23 (November–April) and rabi 2023–24 (November–April) the mean maximum temperature, minimum temperature, relative humidity, wind speed, bright sun shine hours, PAN evaporation, total rainfall, total rainy days were 25.9oC, 11.0oC, 56.8–89.3%, 3.4 km/hr, 6.2 hr/day, 2.7 mm/day, 28.4 mm, 6.0 days and 25.0oC, 10.6oC, 48.0–88.6%, 48.0, 3.3 km/hr, 4.9 hr/day, 2.6 mm/day, 68.6 mm, 5.0 days, respectively. Agronomic management and inputs for irrigation, nutrients, and weed and plant protection for all rabi crops were provided as per the recommended package and practices of CCS Haryana Agricultural University, Hisar.

The energy equivalents of all inputs in the form of labor, seeds, fertilizers, hoeing, implements, and pesticides, and the energy output as produce, were converted into energy (MJ) to calculate the input and output energy of both crop seasons as well as crop rotations, using energy equivalent factors as given by Meena et al. (2024), Devasenapathy et al. (2009), Mittal and Dhawan (1988), Kumar et al. (2022) and Dhaka et al. (2017) in Table 1. Net energy return was calculated as the difference between the total output energy and total input energy. The energy ratio was determined as the energy output divided by input energy. Human energy profitability was calculated by dividing the output energy by labor energy.

Energy productivity was calculated by dividing the grain yield of the crop by its respective input energy requirement. Energy intensity was expressed as the total input energy divided by the cost of cultivation. Energy profitability was computed by dividing the net energy return by the total input energy. Specific energy was calculated by dividing the input energy by the grain yield in kg/ha. The different energy-based indices were calculated as per the procedure given by Devasenapathy et al. (2009) and Mittal and Dhawan (1988) as follows:

Net Energy = Energy output (MJ/ha) _ Energy input (MJ/ha)

Energy use efficiency = Energy output (MJ/ha) /Energy input (MJ/ha)

Energy productivity = Economic yield (t/ha) / Energy input (MJ/ha)

Energy intensiveness = Energy input (MJ/ha) / Total cost (₹/ha)

To compute the relative economics of all crop rotations, the data provided by the Department of Agricultural Economics, CCS Haryana Agricultural University, Hisar, was considered for both the season's crop inputs and outputs. The prices considered for grains of foxtail millet, little millet/browntop millet/proso millet, kodo millet, barnyard millet, finger millet and pearl millet were ₹ 2909, 2300, 2599, 2800, 3578, and 2350/quintal, respectively, while the straw rate was ₹ 1,500/acre. Similarly, the prices used for wheat, raya and chickpea seed were ₹ 2015, 5050 and 5,230/quintal, respectively. While the prices used for wheat, raya and chickpea straw were ₹10,092, 2,100 and 1,558/acre, respectively. The total and variable costs, gross and net returns, B:C ratio and per-day returns for all eight crop rotations were calculated.

RESULTS AND DISCUSSION

Kharif season: Regarding crop duration, yield and yield attributes significant variations were recorded among millets (Table 2). Proso millet took minimum days (69) to mature and it was statistically at par with pearl millet (71) and browntop millet (73), while finger millet took maximum days (116) to mature. Kodo millet and little millet mature in almost the same days (91–92). The variations in maturity periods among millets in Haryana are driven by genetic differences, environmental adaptations and agronomic practices Harish et al., (2024). Pearl millet recorded significantly higher plant height (201.5 cm), while the lowest plant height was recorded with Kodo millet (86.3 cm) which was statistically at par with proso millet. Littile millet, browntop millet and barnyard millet recorded statistically similar plant height. Pearl millet's tall stature reflects its breeding for high yield and biomass, while kodo and proso millets' shorter heights suit low-input, drought-prone systems. Little, browntop, and barnyard millets' similar heights indicate comparable growth strategies in mixed or rainfed systems Harish et al., (2024); Yadav et al., (2024). Significantly smallest ear head length (5.8 cm) was recorded with kodo millet which was statistically at par with finger millet, while proso millet, closely followed by little millet recorded significantly higher ear head length (28.7 cm). Regarding ear head length, non-significant variation was found among pearl millet and foxtail millet, browntop millet and barnyard millet. Significantly higher and lower numbers of tillers and ear heads were recorded with proso millet and finger millet, respectively. Barnyard millet, kodo millet and foxtail millet recorded non-significant variations regarding total number of tillers and ear heads per plant. Similarly, browntop millet, little millet and pearl millets had also recorded statistically similar tillers and ear heads per plant. Pearl millet and little millet recorded significantly higher (6.34 g) and lower (1.91 g) test weights, respectively. Browntop millet, finger millet and barnyard millet recorded statistically similar test weights (3.25–3.29 g). Variations among millets for yield attributes might be due to differences in their genetic makeup and yield potential (Garg et al., 2020; Krishna et al., 2020). Among all millets, Pearl millet recorded significantly higher grain yield (2427 kg/ha), which was 27.4, 74.4, 49.8, 60.4, 35.3, 37.2 and 31.1 percent higher than foxtail millet, little millet, browntop millet, proso millet, kodo millet, finger millet and barnyard millet, respectively. Little millet yielded significantly lower grain yield (621 kg/ha). Kodo millet, finger millet, barnyard millet and foxtail millet had shown non-significant differences regarding grain yield. Similarly, proso millet and browntop millet were also reported with statistically at par yield levels. Similarly, all millets except finger millet have produced significantly lower straw yield than pearl millet. Significantly higher (8,647 kg/ha) and lower (4,466 kg/ha) straw yield were reported with finger millet and foxtail millet, respectively. Pearl millet recorded 41.3, 36.0, 13.4, 38.9, 20.7 and 16.8 percent higher straw yield over foxtail millet, little millet, browntop millet, proso millet, kodo millet and barnyard millet, respectively. Finger millet produced 13.5% higher straw yield than pearl millet. Foxtail millet, little millet and proso millet recorded statistically similar straw yield. Similarly, browntop millet, Kodo millet and barnyard millet had also shown a non-significant difference regarding straw yield. The increase in grain yield of some millets might be due to increased photosynthetic activity, which resulted in a higher accumulation of photosynthates and their translocation to sink due to better source and sink channel Krishna et al., (2020); Reddy et al., (2020). The increase in grain yield could be explained based on their beneficial effects on yield-attributing characteristics Hemalatha et al., (2021). Nalini et al. (2020) in a study on pearl millet, Hemalatha et al. (2021) in a study on kodo millet, Krishna et al. (2020) in a study on finger millet and Reddy et al. (2020) in a study on foxtail millet have also reported similar findings.

Rabi season: Effective tillers, test weight and yield of wheat were significantly affected by the preceding millet crops. Spike length was non significantly affected by preceding millets (Table 3). Significantly higher (121.9) and lower (79.1) effective tillers/mrl were noticed with wheat sown after little millet and finger millet, respectively. Wheat preceded by pearl millet, foxtail millet, kodo millet and barnyard millet had shown non-significant differences regarding effective tillers Significantly higher test weight (35.8 g) was recorded with wheat sown after finger millet, while wheat preceded by browntop millet recorded significantly lower test weight (32.2 g). Wheat preceded by pearl millet, foxtail millet, proso millet, finger millet and barnyard millet had shown non-significant differences regarding test weight. Wheat sown after proso millet, closely followed by wheat, preceded by pearl millet, recorded significantly higher grain yield (6,249 kg/ha), while wheat sown after finger millet was recorded with significantly lower grain yield (3,123 kg/ha). Wheat preceded by pearl millet recorded 15.6, 15.2, 4.9, 10.2, 49.4 and 7.8% higher grain yield over the wheat sown after foxtail millet, little millet, browntop millet, kodo millet, finger millet and barnyard millet, respectively. Wheat sown after pearl millet, browntop millet, proso millet, kodo millet and barnyard millet had shown non-significant differences regarding grain yield. Similarly, wheat preceded by foxtail millet, little millet, browntop millet, kodo millet and barnyard millet had also reported with statistically at par yield levels. Wheat sown after barnyard millet recorded with significantly higher straw yield (8,024 kg/ha), which was statistically at par with wheat preceded by all millets except little millet and finger millet. Wheat sown after finger millet recorded significantly lower straw yield (2,221 kg/ha). The lower yield and yield attributes recorded with wheat preceded by finger millet might be due to the delayed sowing of wheat after finger millet compared to other millets Yusuf et al., (2019); Choudhary et al., (2018).

All yield attributes and yield of Indian mustard were significantly affected by the preceding millet crops (Table 3). Significantly higher (5.48 cm) and lower (1.92 cm) siliqua length were noticed with Indian mustard preceded by kodo millet and finger millets, respectively. Indian mustard sown after browntop millet, proso millet and barnyard millet had shown non-significant variations regarding siliqua length. Similarly, siliqua length recorded with Indian mustard preceded by pearl millet and little millet, foxtail millet and finger millet had also been reported with non-significant differences. Significantly higher (251.5) and lower (78.3) silique per plant were noticed with Indian mustard sown after pearl millet and finger millet, respectively. Indian mustard preceded by pearl millet, browntop millet and barnyard millet had shown non-significant differences regarding silique per plant. Similarly, Indian mustard sown after foxtail millet, little millet, kodo millet and proso millet had shown nonsignificant differences regarding silique per plant. Significantly higher test weight (6.38 g) was recorded with Indian mustard sown after browntop millet, while Indian mustard preceded by finger millet recorded significantly lower test weight (5.21 g). Indian mustard preceded by little millet, browntop millet, proso millet, kodo millet and barnyard millet had shown non-significant differences regarding test weight. Similarly, test weight recorded with Indian mustard sown after pearl millet and foxtail millet was also found statistically at par. Indian mustard sown after pearl millet, closely followed by Indian mustard, preceded by foxtail millet recorded significantly higher grain yield (2,522 kg/ha), while Indian mustard sown after finger millet was recorded with significantly lower grain yield (304 kg/ha). Indian mustard preceded by pearl millet recorded 2.8, 50.3, 40.4, 19.2, 47.2, 87.9 and 9.0% higher grain yield over the Indian mustard sown after foxtail millet, little millet, browntop millet, proso millet, kodo millet, finger millet and barnyard millet, respectively. Indian mustard sown after little millet, browntop millet and kodo millet had shown non-significant differences regarding grain yield. Similarly, Indian mustard preceded by proso millet and barnyard millet had also reported with statistically at par grain yield levels. Indian mustard sown after foxtail millet closely followed by Indian mustard preceded by pearl millet recorded with significantly higher straw yield (13,176 kg/ha), while Indian mustard sown after finger millet recorded significantly lower straw yield (1,243 kg/ha). The lower yield and yield attributes recorded with Indian mustard preceded by finger millet attributed to the delayed sowing of Indian mustard after finger millet compared to other millets Yang et al., (2014); Miller et al., (2003).

Pods per plant, seed index and yield of chickpea were significantly affected by the preceding millet crops. Pod length was non significantly affected by preceding millets, while numerically higher and lower pod length were noticed with chickpea preceded by kodo millet and finger millet, respectively. Chickpea sown after pearl millet recorded significantly higher (122.8) pods per plant and it was statistically at par with chickpea preceded by barnyard millet. Significantly lower (73.7) pods/plant were noticed with chickpea sown after finger millet and it was statistically at par with chickpea sown after foxtail millet, browntop millet and proso millet. Similarly, chickpea preceded by little millet and kodo millet had sown non-significant differences regarding pods/plant. Significantly higher seed index (15.9 g) was recorded with chickpea sown after pearl millet and barnyard millet, while chickpea preceded by finger millet recorded significantly lower seed index (13.7 g). Chickpea preceded by all millets except finger millet had shown non-significant differences regarding seed index. Chickpea sown after pearl millet closely followed by chickpea preceded by barnyard millet recorded significantly higher grain yield (1,842 kg/ha), while chickpea sown after finger millet was recorded with significantly lower grain yield (684 kg/ha). Chickpea preceded by pearl millet recorded 15.6, 25.8, 4.9, 11.2, 13.8, 22.2, 62.8 and 4.6% higher grain yield over the chickpea sown after foxtail millet, little millet, browntop millet, proso millet, kodo millet, finger millet and barnyard millet, respectively. Chickpea sown after foxtail millet, little millet, browntop millet, proso millet and kodo millet had shown non-significant differences regarding grain yield. Chickpea sown after browntop millet recorded with significantly higher straw yield (5,276 kg/ha), which was statistically at par with chickpea preceded by all millets except little millet, kodo millet and finger millet. Chickpea sown after finger millet recorded significantly lower straw yield (1,633 kg/ha). The lower yield and yield attributes recorded with chickpea preceded by finger millet might be due to the delayed sowing of chickpea after finger millet, compared to other millets. The synergistic cereal–legume association leads to soil-N enrichment by biological-N fixation under legume cultivation and microbial activity in the rhizosphere (Sodavadiya et al., (2023); Faiz et al., (2022).

Crop Rotations: Total duration of different millet-based crop rotations with wheat, Indian mustard and chickpea has shown significant variations (Table 4). Among millet-based crop rotations with wheat, little millet-wheat and pearl millet-wheat rotations were recorded with significantly higher (256 days) and lower (230 days) duration, respectively. Pearl millet-wheat and proso millet-wheat rotations recorded statistically at par duration. Similarly, wheat preceded by foxtail millet/ finger millet/ barnyard millet had also been recorded with statistically similar duration (140 days). Proso millet-Indian mustard, closely followed by pearl millet- Indian mustard and kodo millet-Indian mustard, closely followed by finger millet-Indian mustard crop rotations were recorded with significantly lower (211 days) and higher (242 days) crop duration, respectively. Similarly, Kodo millet/little millet-chickpea and proso millet-chickpea crop rotations were reported with significantly higher (250 days) and lower (232 days) duration, respectively. Out of all millet crop rotations with wheat/Indian mustard/chickpea, the Proso millet/pearl millet and little millet/kodo millet-based crop rotations took minimum and maximum duration up to maturity, respectively.

Among all crop rotations except finger millet-wheat, Pearl millet-based crop rotations with wheat/Indian mustard/chickpea recorded significantly higher wheat equivalent yield (9,002 kg/ha)/Indian mustard equivalent yield (3,651 kg/ha)/chickpea equivalent yield (2,933 kg/ha), respectively. Little millet crop rotation with wheat and chickpea recorded significantly lower wheat equivalent yield (5,940 kg/ha) and chickpea equivalent yield (1,638 kg/ha), respectively, while in case of Indian mustard it was found to be lower (1,385 kg/ha) with finger millet-Indian mustard rotation. Crop equivalent yield varied non significantly among all millet-based crop rotations with wheat, except pearl millet/finger millet/little millet-wheat rotations. Similarly, Pearl millet/barnyard millet-Indian mustard/ chickpea crop rotations, little millet/finger millet-Indian mustard/ chickpea crop rotations and browntop millet/proso millet/kodo millet- Indian mustard/ chickpea crop rotations had shown non-significant variation among themselves regarding respective crop equivalent yield. Corroborative findings have also been reported by Jat et al., (2024); Choudhary et al., (2016).

Irrespective of millets, the millet-based crop rotations with wheat demanded higher cost compared to millet-based crop rotations with Indian mustard/chickpea. On economic basis, it was found that irrespective of millets, the millet-based crop rotations with Indian mustard recorded higher net returns, B:C and per-day returns compared to millet-based crop rotations with wheat and chickpea. Among all crop rotations, finger millet-wheat/Indian mustard/chickpea recorded higher (143.7/123.3/108.4 × 103 ₹/ha) and foxtail millet-wheat/Indian mustard/chickpea recorded lower (132.3/111.8/96.9 × 103 ₹/ha) total cost, respectively. Significantly higher and lower gross returns, net returns, B:C and per day returns were recorded with Pearl millet-wheat/Indian mustard/chickpea and Finger millet-wheat/Indian mustard/chickpea crop rotations, respectively. Pearl millet- wheat closely followed by barnyard millet- wheat crop rotation recorded significantly higher gross returns (210.4 × 103 ₹/ha), net returns (71.5 × 103 ₹/ha), B:C (1.52) and per day returns (311 ₹/day/ha), while Finger millet- wheat crop rotation recorded significantly lower gross returns (146.5 × 103 ₹/ha), 2.7 × 103 ₹/ha), B:C (1.02) and per day returns (11 ₹/day/ha). Similarly, Pearl millet-Indian mustard and Pearl millet-chickpea crop rotation recorded significantly higher gross returns (193.4 and 161.0 × 103 ₹/ha), net returns (75.0 and 57.5 × 103 ₹/ha), B:C (1.65 and 1.56) and per day returns (351 and 245 ₹/day/ha), while Finger millet-Indian mustard and Finger millet-chickpea crop rotation recorded significantly lower gross returns (78.9 and 98.0 × 103 ₹/ha), net returns (–44.3 and –10.4 × 103 ₹/ha), B:C (0.64 and 0.90) and per day returns (–184 and –43 ₹/day/ha). Our of all crop rotations studied, pearl millet- Indian mustard closely followed by foxtail millet- Indian mustard was found most economical with 4.8 and 30.4% higher net returns, 8.5 and 5.8% higher B:C, 12.9 and 43.2% higher returns per day than pearl millet–wheat and pearl millet–chickpea, respectively. Little millet/finger millet–Indian mustard/chickpea rotations proved most uneconomical. These results are in close conformity with the findings of Bana et al. (2023), Sharmili et al. (2023), Mohan et al. (2019).

Among all millet-based crop rotations with wheat/Indian mustard/chickpea significant variations were found regarding input energy, output energy and net energy return (Table 5). Pearl millet followed by wheat/Indian mustard/chickpea rotations were recorded with significantly higher input energy (28.6/19.9/16.3 × 103 MJ/ha), output energy (303.3/324.4/205 × 103 MJ/ha) and net energy returns (274.6/304.5/188.7 × 103 MJ/ha), respectively. All millet except pearl millet and finger millet-based crop rotations with wheat/Indian mustard/chickpea were reported with statistically at par input energy, output energy and net energy returns. Irrespective of millets, the millet-based crop rotations with wheat demanded 43.7 and 75.4% higher input energy compared to millet-based crop rotations with Indian mustard and chickpea, respectively. While, irrespective to millets, the millet-based crop rotations with Indian mustard recorded 6.9 and 58.2% higher output energy, 10.8 and 61.3% higher net energy returns, 53.7 and 29.41% higher energy ratio compared to millet-based crop rotations with wheat and chickpea, respectively. Significantly lower output energy and energy returns were recorded with finger millet-wheat/Indian mustard and little millet-chickpea rotations. Significant variations among all crop rotations were found regarding energy ratio, energy productivity, energy profitability and specific energy. Barnyard millet-wheat, foxtail millet-Indian mustard and brown top millet-chickpea rotations recorded significantly higher energy ratio valued 11.19, 16.46 and 14.28, respectively, while finger millet-wheat/Indian mustard and little millet-chickpea were reported with significantly lower energy ratio. Pearl millet/brown top millet/barnyard millet-wheat, pearl millet/foxtail millet/barnyard millet- Indian mustard and brown top millet/barnyard millet-chickpea rotation had shown non-significant variations among themselves for energy ratio. Pearl millet-wheat/Indian mustard/chickpea recorded significantly higher energy productivity and significantly lower specific energy. While finger millet-wheat/ Indian mustard rotations recorded significantly lower energy productivity, energy profitability, it was also reported with significantly higher specific energy. Similarly, Little millet-chickpea recorded significantly lower energy productivity and energy profitability, while finger miller-chickpea reported significantly higher specific energy. Irrespective of millets, the millet-based crop rotations with wheat recorded 20 and 15.4% higher energy productivity compared to millet-based crop rotations with Indian mustard and chickpea, respectively. While, irrespective of millets, the millet-based crop rotations with Indian mustard recorded 59.3 and 31.9% higher energy profitability, 27.4 and 11.2% higher specific energy compared to millet-based crop rotations with wheat and chickpea, respectively. These results conformed with the findings of Kargwal et al. (2023); Kumar et al. (2022); Choudhary et al. (2017) and Singh et al. (2007).

It was concluded that, irrespective of millets, the millet-based crop rotations with Indian mustard recorded higher economic and energy returns compared to millet-based crop rotations with wheat and chickpea. Out of all crop rotations studied, pearl millet- Indian mustard closely followed by foxtail millet- Indian mustard was found most economical and energy efficient with 4.8 and 30.4% higher net returns, 8.5 and 5.8% higher B:C, 12.9 and 43.2% higher returns per day, 6.9 and 58.2 percent higher output energy, 10.8 and 61.3% higher net energy returns than pearl millet- wheat and pearl millet- chickpea crop rotations, respectively. Among all millet-based crop rotations, Pearl millet followed by wheat/Indian mustard/chickpea rotations were recorded with significantly higher net returns, B:C and per day returns, output energy and net energy returns, respectively. Little millet/finger millet-Indian mustard/chickpea rotations proved most uneconomical. So, the millet growers of semi-arid areas of Haryana may go for Pearl millet/Foxtail millet-based crop rotations with Indian mustard to make their crop rotations economically profitable and energy efficient.

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Table 1. Equivalent coefficient for various input sources of energy used for energy calculation under different cropping sequences

Inputs	Unit	Energy Equivalent (MJ/unit)	References
Human labour			
Human labour (Male)	h	1.96	Ghosh et al. (2021)
Human labour (Female)	h	1.57	Ghosh et al. (2021)
Harvesting	h	1.96	Singh and Mittal (1992)
Spraying	h	1.96	Ram and Verma (2015)
Transportation	kg	1.08	Pimentel and Burgess (1980)
Irrigation Water	m³	1.02	Tuti et al. (2012)
Cultural practices	h	1.96	Singh and Mittal (1992)
Machinery			
Sprayer	h	0.50	Nassiri and Singh (2010)
Tractor	h	64.80	Pathak et al. (2022)
Sickle	h	0.83	Nassiri and Singh (2010)
Farm machinery	kg	62.70	Tuti et al. (2012)
Electricity	KWH	11.93	Ozkan et al. (2004)
Electric motor (2 HP)	kg	64.80	Devasenapathy et al. (2009)
Machinery (All kind)	kg	68.40	Singh and Mittal (1992)
Diesel	l	56.31	Canakci and Akinci (2003)
Chemical fertilize₹			
Nitrogen (N)	kg	60.6	Toader and Gheorghe (2014)
Phosphorus (P_2O_5)	kg	11.1	Toader and Gheorghe (2014)
Potassium (K_2O)	kg	6.7	Devasenapathy et al. (2009)
Zinc sulphate ($ZnSO_4$)	kg	20.9	Singh and Mittal (1992)
Gypsum	kg	10	Devasenapathy et al. (2009)
Superior chemical	kg	120	Devasenapathy et al. (2009)
Plant protection			
Fungicide	kg	97	West and Marland (2002)
Herbicides	kg	288	Pimentel and Burgess (1980)
Insecticide	kg	237	West and Marland (2002)
Organic fertilize₹			
Manure/FYM	kg	0.30	Tuti et al. (2012)
Vermicompost	kg	0.50	Ram and Verma (2015)
Biofertilizers	kg	2.98	Mihov et al. (2012)
Wheat seed	kg	14.7	Singh and Mittal (1992)
Chickpea seed	kg	25.0	Thyagaraj (2012)
Pearl millet	kg	14.7	Devasenapathy et al. (2009)
Mustard seed	kg	25.0	Singh and Mittal (1992)
Stover/stalk	kg	12.5	Devasenapathy et al. (2009)

Table 2. Comparative yield performance of millets in Hisar district of Haryana (pooled mean data of 2 years)

Millets	Total duration (days)	Yield attributes per plant					Grain yield (kg/ha)	Straw yield (kg/ha)
		Plant height (cm)	Ear head length (cm)	Tillers (nos.)	Ear heads (nos.)	Test weight (g)		
Pearl millet	71	201.5	21.0	29.2	21.2	6.34	2,427	7,615
Foxtail millet	78	179.5	20.2	18.5	15.5	2.52	1,762	4,466
Little millet	92	161.5	27.2	25.2	15.5	1.91	621	4,869
Browntop millet	73	160.7	17.1	23.8	19.0	3.29	1,217	6,592
Proso millet	69	93.0	28.7	86.5	77.3	4.35	960	4,652
Kodo millet	91	86.3	5.8	18.3	15.2	4.82	1,568	6,041
Finger millet	116	106.0	7.0	8.3	7.7	3.25	1,525	8,647
Barnyard millet	78	155.2	16.8	17.0	12.7	3.28	1,672	6,331
SEm±	2.1	4.0	0.7	1.6	1.8	0.05	92	190
LSD (P=0.05)	6.7	12.1	2.2	5.0	5.6	0.15	282	583

Table 3. Yield performance of Rabi crops preceded by different millets (Pooled mean data of 2 years)

Millets	Wheat					Indian Mustard					Chickpea				
	Spike length (cm)	Effective tillers/mrl (nos.)	Test weight (g)	Grain yield (kg/ha)	Straw yield (kg/ha)	Siliqua length (cm)	Silique/plant (nos.)	Test weight (g)	Grain yield (kg/ha)	Straw yield (kg/ha)	Pod length (cm)	Pos/plant (nos.)	100 seed weight (g)	Grain yield (kg/ha)	Straw yield (kg/ha)
Pearl millet – Rabi crop	10.1	104.1	35.4	6,171	6,535	4.03	251.5	5.89	2,522	12,557	1.47	122.8	15.9	1,842	3,767
Foxtail millet - Rabi crop	9.4	106.8	35.0	5,203	7,484	2.02	201.2	5.90	2,450	13,176	1.48	80.4	15.5	1,553	4,862
Little millet - Rabi crop	11.3	121.9	33.3	5,232	5,943	4.25	186.8	6.06	1,251	5,495	1.52	95.0	15.7	1,365	3,224
Browntop millet-Rabi crop	10.1	118.8	32.2	5,865	7,510	4.96	223.4	6.38	1,503	8,857	1.47	86.8	15.8	1,635	5,276
Proso millet - Rabi crop	9.3	85.4	34.2	6,249	6,844	4.81	184.6	6.19	2,037	10,010	1.38	76.4	14.9	1,587	4,905
Kodo millet - Rabi crop	11.1	107.9	32.9	5,540	6,786	5.48	209.7	6.01	1,331	5,700	1.55	97.2	15.7	1,433	2,262
Finger millet - Rabi crop	8.8	79.1	35.8	3,123	2,221	1.92	78.3	5.21	304	1,243	1.21	73.7	13.7	684	1,633
Barnyard millet - Rabi crop	10.7	109.1	34.7	5,691	8,024	4.74	235.1	6.28	2,293	10,595	1.52	117.6	15.9	1,757	3,802
SEm±	0.57	2.45	0.68	325	639	0.14	12.5	0.14	137.0	475.9	0.07	4.9	0.32	76	547
LSD (P=0.05)	NS	7.50	2.10	996	1,959	0.42	38.3	0.44	419.7	1,457.6	NS	15.1	0.99	232	1,675

Table 4. Duration, Crop Equivalent yield and Economics of millet-based crop rotations (Pooled mean data of 2 years)

Treatments	Total duration (days)			Crop Equivalent Yield (Kg/ha)			Total Cost (₹ × 103/ha)			Gross return (₹ × 103/ha)			Net returns (₹ × 103/ha)			B:C Ratio			Per day return (₹/day/ha)		
	W	M	CP	W	M	CP	W	M	CP	W	M	CP	W	M	CP	W	M	CP	W	M	CP
Pearl millet –RC	230	213	235	9,002	3,651	2,933	138.9	118.4	103.6	210.4	193.4	161.0	71.5	75.0	57.5	1.52	1.65	1.56	311	351	245
Foxtail millet-RC	240	220	238	7,748	3,465	2,533	132.3	111.8	96.9	185.1	184.0	140.1	52.8	72.2	43.2	1.4	1.63	1.45	220	328	181
Little millet- RC	256	240	250	5,940	1,534	1,638	132.7	112.2	97.4	148.7	86.5	93.3	16.0	-25.7	-4.0	1.12	0.77	0.96	63	-107	-16
Browntop millet- RC	235	214	236	7,254	2,057	2,170	135.8	115.3	100.5	175.2	112.9	121.1	39.4	-2.4	20.7	1.29	0.98	1.21	168	-11	88
Proso millet - RC	231	211	232	7,345	2,474	2,009	134.5	114.0	99.1	177.0	133.9	112.7	42.5	20.0	13.6	1.32	1.18	1.14	184	95	59
Kodo millet - RC	253	242	250	7,557	2,136	2,213	132.5	112.0	97.2	181.3	116.9	123.3	48.7	4.9	26.1	1.37	1.04	1.27	193	20	104
Finger millet - RC	240	241	241	11,188	1,385	1,728	143.7	123.3	108.4	146.5	78.9	98.0	2.7	-44.3	-10.4	1.02	0.64	0.9	11	-184	-43
Barnyard millet - RC	240	220	242	8,015	3,221	2,652	134.1	113.6	98.8	190.5	171.7	146.4	56.4	58.1	47.6	1.42	1.51	1.48	235	263	197
SEm±	1.05	0.83	0.66	474	151	95	-	-	-	8.2	7.6	5.0	8.2	7.6	5.0	0.06	0.07	0.05	34	35	21
LSD (P=0.05)	3.24	2.56	2.03	1,452	462	291	-	-	-	25.1	23.4	15.2	25.1	23.4	15.2	0.18	0.2	0.15	105	106	63

Table 5. Energy-based indices of millet-based crop rotations (pooled mean data of 2 years)

Treatment	Input energy (× 103 MJ/ha)			Output energy (× 103 MJ/ha)			Net energy returns (× 103 MJ/ha)			Energy ratio			Energy Productivity (Kg/MJ)			Energy Profitability (MJ/ha)			Specific energy (MJ/kg)		
	W	M	CP	W	M	CP	W	M	CP	W	M	CP	W	M	CP	W	M	CP	W	M	CP
Pearl millet – RC	28.6	19.9	16.3	303.3	324.4	205.0	274.6	304.5	188.7	10.59	16.28	12.58	0.30	0.25	0.26	9.59	15.28	11.58	3.35	4.26	3.83
Foxtail millet- RC	25.7	17.0	13.4	251.8	279.6	165.3	226.1	262.6	152.0	9.80	16.46	12.38	0.27	0.24	0.25	8.80	15.46	11.38	3.74	4.31	4.04
Little millet- RC	25.7	17.0	13.3	221.2	157.3	130.4	195.5	140.3	117.0	8.61	9.27	9.77	0.23	0.11	0.15	7.61	8.27	8.77	4.43	9.20	6.86
Browntop millet- RC	25.7	17.0	13.3	280.4	233.4	190.3	254.7	216.5	177.0	10.92	13.76	14.28	0.28	0.16	0.21	9.92	12.76	13.28	3.76	6.86	4.78
Proso millet - RC	25	17	13	24	22	156.9	22	20	143.4	9.64	13.	11.59	0.28	0.16	0.	8.64	12.	10.59	3.	6.74	5.36

	.9	.2	.5	9.7	3.9		3.8	6.7			03				19		03		61		
Kodo millet - RC	25.7	17.0	13.4	264.8	189.6	147.9	239.1	172.6	134.6	10.30	11.16	11.08	0.28	0.17	0.23	9.30	10.16	10.08	3.63	6.23	4.94
Finger millet - RC	26.4	17.7	14.0	204.2	150.5	161.0	177.8	132.9	147.0	7.74	8.53	11.49	0.18	0.10	0.16	6.74	7.53	10.49	6.13	10.61	7.59
Barnyard millet - RC	25.7	17.0	13.4	287.7	269.4	177.1	262.0	252.4	163.7	11.19	15.86	13.26	0.29	0.23	0.26	10.19	14.86	12.26	3.60	4.66	3.92
SEm±	0.1	0.1	0.1	7.0	6.4	7.2	7.0	6.4	7.2	0.27	0.37	0.52	0.02	0.01	0.01	0.27	0.37	0.52	0.25	0.38	0.32
CD (P=0.05)	0.2	0.3	0.2	21.3	19.7	22.0	21.3	19.7	22.0	0.81	1.14	1.59	0.05	0.03	0.03	0.81	1.14	1.59	0.75	1.17	0.97

Note, RC, rabi crop, W, wheat; M, Mustard; CP, Chickpea