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Optimizing little millet and red gram mixtures to improve the system productivity and soil fertility of rain-dependent alfisol of semi-arid India

Kannan Pandian*[1], Sivakami Kannan[2], Vijayakumar Mathiyazhagan[3] and Swaminathan Chitraputhirapillai [4]

[1] Department of Soils and Environment, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai - 625104, Tamil Nadu, India.
[2] Centre of Excellence in Millets, Tamil Nadu Agricultural University, Athiyandal - 606603, Tamil Nadu, India.
[3] Agricultural College and Research Institute, Tamil Nadu Agricultural University, Kudimiyanmalai - 625104, Tamil Nadu, India.
[4] Department of Agronomy, Water Technology Center, Tamil Nadu Agricultural University, Coimbatore - 641003, Tamil Nadu, India.
***** Corresponding author; e-mail: kannan.p@tnau.ac.in

ABSTRACT

The vagaries of monsoon rains severely affect the growth and yield of little millet (*Panicum sumatrense*) in semi-arid India. Continuous sole cultivation of little millet depletes soil nutrients, reduces crop productivity, and fails to ensure a stable income for farmers. A crop mixer is an alternate option to cope with climate variability and sustain soil fertility in the sole crop little millet areas. Among crops, pulse crops are a viable mixer for improving soil fertility, productivity and farmers' net income. Field studies were conducted in 2016, 2017, and 2018 at the Dryland Agricultural Research Station, India. Little millet was raised as the main crop, with red gram intercropped in ratios of 4:1, 6:2, and 8:2. Black gram, moth bean, and horse gram were sequentially cultivated after the little millet harvest. Biometric, yield attributes and yield, soil nutrients and nutrient uptake were measured. Intercropping of little millet and redgram in a 4:1 combination recorded higher grain yield (511 kg ha^{-1}) and straw yield (1632 kg ha^{-1}) of little millet. Similarly, little millet grain equivalent yield and production efficiency were also higher (730 kg ha^{-1} & 4.5 kg ha^{-1} day^{-1}) in the 4:1 combination with sequential horse gam. Regarding soil fertility, a 4:1 combination with sequential horse gram resulted in significant nitrogen build-up (157.3 kg ha^{-1}) and phosphorus (9.7 kg ha^{-1}) and potassium uptake (37.6 kg ha^{-1}). Intercropping red gram with little millet at a 4:1 ratio, followed by sequential planting of horse gram, enhances rainfed little millet pulse productivity and improves soil fertility in semi-arid Alfisol.

Keywords: Intercrop, Little millet, Nutrient balance, Production efficiency, Rainfed, Sequential crop.

1. INTRODUCTION

Growing legumes and cereals in mixtures with or without definite spacing has been a long-standing practice in tropical agriculture dating back to ancient civilizations. The main purpose of mixing crops is to make the best use of physical resources like space, light and nutrients (Willey, 1990; Li et al., 2007), besides improving the quality and quantity of output (Singh and Ahlawat, 2011). Other benefits include reducing the use of inorganic nitrogen fertilizers that pollute the environment (Singh and Ahlawat, 2011), and ensuring sustainable and environmentally friendly cropping systems (Singh et al., 2016). The renewed interest in cropping systems research indicates that when two crops are planted together, interspecific competition or facilitation between plants may occur (Yang, 2020; Singh et al., 2013) and thereby result in higher grain yields than either crop grown alone (Mead and Willey, 1980; Dapaah et al., 2003). In such crop mixtures, the yield increase may be not only due to improved nitrogen nutrition of the cereal component but also to other unknown causes (Connolly et al., 2001; Singh et al., 2014).

Under mixed cultures, the crop mixtures naturally manage the system with the alteration of microclimatic conditions, better recycling of soil nutrients, superior soil quality, and stabilisation of soil. However, if the mixtures are grown as intercrops in definite row arrangements will facilitate for optimal use of spatial, temporal, and physical resources by main and intercrop, resulting in synergistic above and below-ground components positive interactions (facilitation). Another sociological reason is that yields under rainfed situations in semi-arid climates have positive relations with the rainfall and its distribution and air temperature, which eventually impinge on the economics of rainfed farmers (Gadedjisso-Tossou, 2021). Furthermore, the increased market price and better yield potential favoured wider cereal grain production and coverage of a cultivable area. At the same time, due to its lower financial return than rice, native and drought-tolerant millet crop output and area decreased (Eliazer Nelson et al., 2019). Millets can grow on arid lands with minimal inputs and are resilient to changes in climate. The multifaceted benefit of millet should reach the global community to combat malnutrition, create awareness and increase the production and consumption of millets, the United Nations declared 2023 the International Year Millets. The pressure of excessive carbohydrate consumption, putting diabetics among the rice-eating population across the globe, has realised the unconstructive influence of cereal food and is now slowly revisiting the traditional nutri-millets, which are rich in minerals and fibre (Maitra and Shankar, 2019).

Millets are vital for low-income farmers in hot, dry regions of Africa and Asia, where over 97% of millet production and consumption occurs (McDonough et al., 2000). Millets are small-seeded grasses widely grown across the world as cereal crops or grains for fodder and human food. Various types of millet crops, such as sorghum (*Sorghum bicolor* (L.)), finger millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*), barnyard millet (*Echinochloa colona*), kodo millet (*Paspalum scrobiculatum*), proso millet (*Panicum miliaceum*), and little millet (*Panicum miliare*), are grown across the globe. Nutri millets are traditional cereal crops, which are grown in arid and semi-arid zones as rainfed crops, under marginal and submarginal conditions of soil fertility and moisture. However, it's crucial to recognize that despite these difficulties, the average grain yield remains impressively high, nearly reaching 1000 kg per hectare. Recognizing this, there's a growing awareness of the need for increased research and development for these crops. According to FAOSTAT (2018), there has been a decline of 25.7% in the global area under millet cultivation from 1961 to 2018, and the largest area reduction was observed in Asia, whereas the lowest was observed in Africa. Little millet, a hardy crop with a short life, is grown entirely in rainfed conditions (Vetriventhan et al., 2020), with a production capacity of 1600 kg ha^{-1}, but farmers only obtain 750 kg ha^{-1} due to erratic monsoon rains and a lack of adoption of improved soil and crop production technologies (Tadele, 2016).

Red gram is a promising intercrop in a rainfed environment; being a hardy crop for a long time, the deep-rooted, nitrogen-fixing hardy crop is chosen for the study. Besides this, it adds a substantial quantity of organic matter, thereby contributing to organic carbon build-up (Zhao et al., 2020). Though there is a lot of literature available for different cereal legume research, information on little millet, intercrop redgram and sequential pulses mixture is very scant. As a result, this study was designed to introduce redgram, a long-duration pulse crop, into short-lived millet cultivation with varying population densities and short-duration pulses after the harvest of little millet under rainfed conditions. Furthermore, in the proposed intercropping system of redgram with little millet, the little millet will be harvested in 3 months, at the time, redgram will be in the flowering phase, thereby the competition is nil between these two crops at the time of maturity for resources. Based on the positive benefits of intercropping and to enhance the soil fertility, nutritional security and economics of rainfed farmers, we evaluated intercropping redgram at different ratios with little millet and short-lived pulses as sequential crops to optimize the little millet and redgram mixture ratio with a suitable sequential crop for improving system productivity and soil fertility under rainfed conditions.

2. MATERIALS AND METHODS

2.1 Site description and weather conditions

The experiment site (10.16°N, 78.78°E) was situated on the southern plain with an elevation of 116 MSL in Dryland Agricultural Research Station, Chettinad, Tamil Nadu, Southern India. The rainfall received during the experimental period is depicted in Figure 1. The location had a mean annual rainfall of 940 mm and the mean maximum and minimum temperatures during the crop periods were 32.5ºC and 23.6ºC respectively. Experimental soil is acidic and classified as *Typic Haplustalf*. The initial soil properties of the experimental soil are given in Table 1.

2.2 Experimental design

Field experiments were conducted for three consecutive years from 2016 to 2018. Each year, the crops were raised during the monsoon rains i.e., June to September. The experiments were set up in a randomized block design with three replications. In each block, little millet (*saamai-Panicum sumatrense*) cv. CO6 was raised as the main crop at a spacing of 25 cm x10 cm, and redgram (*Cajanus cajan*) cv. VBN3 was grown as intercrop at 4:1(526 Little millet:20 Redgram), 6:2(490 Little millet:26 Redgram) and 8: 2 ratios (515 Little millet:18 Redgram), representing different population densities in a 20 m^2 plot size (5mx4m). After the harvest of little millet, horse gram (*Macrotyloma uniflorum*), black gram (*Vigna mungo*), and moth bean (*Vigna aconitifolia*) were grown as sequential crops. Two border lines of little millet were maintained on both sides of the plot to eliminate edge effects. The sole crop of little millet was maintained separately in the experimental plot and used for growth and yield data observations. The dates of sowing, harvests, rainfall and rainy-day details are presented in Table 2. The soil-test-based fertilizer (40:20:20 NPK kg ha^{-1}) was applied as basal manually each year before the sowing of little millet as per the crop production manual. To supply 20 kg phosphorus, 43.4 kg diammonium phosphate was applied, which supplied 7.8 kg nitrogen and the remaining 32.2 kg nitrogen was supplied through 70 kg urea. Potassium was supplied through 33.2 kg muriate of potash.

2.3 Soil and plant analysis

Soil samples were collected, before seeding, at 15 cm soil depth and soil physicochemical properties were analyzed and presented in Table 1. Each year, after harvesting the crops, four soil samples were taken from each plot at a depth of 0-15 cm using an auger. The collected soil samples were mixed well and representative single representative composite soil sample was prepared for each plot. Composite soil samples were air-dried, ground and passed through a 2.0 mm sieve and used for soil physicochemical analysis.

Soil organic carbon content was analyzed by the Walkley-Black method (Walkley and Black, 1934). Soil available nitrogen (SAN) was estimated by the alkaline potassium permanganate method (Subbiah and Asija, 1956) in which 10 g of soil was treated with an excess of 0.32 % alkaline permanganate and distilled in the presence of 2.5% NaOH. Soil available phosphorous (SAP) was measured by the Bray and Kurtz No. 1 method (Olsen and Sommers, 1982). An extract was prepared from 5 g of soil and reacted with Bray 1 reagent (0.03 N NH4F and 0.02 N HCl). The blue color was developed by the ascorbic method and its intensity was measured at 660 nm in a UV-VIS Spectrophotometer (Jetways 6203 model). Soil available potassium was estimated by the ammonium acetate method (Knudsen et al., 1983). The total N content in plant and seed samples was analyzed using an automated Kjelplus N analyzer (Bremner and Mulvaney, 1982); total P content was analyzed by developing Barton's yellow colour, assessed using Jetways 6203 UV spectroscopy (Olsen and Sommers, 1982) and total K content was quantified using a flame photometer. The acquisition of nitrogen (N), phosphorus (P), and potassium (K) was calculated by multiplying the concentrations of N, P, and K by the straw and grain yields of the respective crops. The nutrient balance was calculated by subtracting the post-harvest soil nutrient status from the initial soil nutrient status of the experimental plots.

2.4 Crop data collection

Five plants were randomly selected and tagged in each plot for crop growth and yield characteristics like plant height, the number of productive tillers, SPAD value, leaf area and days to 50% flowering, test weight, panicle length and panicle weight were measured during the peak vegetative and maturity stages of little millet. The growth and yield parameters of redgram and sequential pulse crops were recorded at flowering and harvest. The chlorophyll content was measured at the peak vegetative stage (45 Days after sowing) in fully opened 4th and 3rd leaf from the top from 10.30 am to 12.30 pm using a Minolta Model 502 SPAD Meter. Seed yield and dry matter production (whole plant dry weight) were recorded from 20 m2 (5 m × 4 m) plots. Seeds were sun-dried and weighed at 10 % moisture. For dry matter production assessment, 10 plants selected were dried in a hot air oven and weighed, and tissue moisture content was corrected for the entire plot plant weight.

The little millet equivalent yield (LMEY) of the intercropping system was calculated by considering the seed yield of component crops and the prevailing market price of both millet and pulse crops by using the following formulas (Lal et al., 2017). The land equivalent ratio was calculated by dividing the intercropped yield by sole crops yield (Mead and Willey, 1980), Land use efficiency (LUE) was worked out by dividing the total duration of crops in a cropping system by the total day in the year (365 days) outlined by Jamwal (2001). The production efficiency (PE) was assessed by dividing the mean yield of sole crops by the mean yield of crops in the mixtures (Agegnehu et al., 2006).

Little millet equivalent yield (LMEY)= $(Y_L+(Y_R x P_R)/P_L)$, Where Y_L and Y_R are the yields of little millet and redgram and P_R and P_L are the current market price of the little millet and redgram

Land equivalent ratio (LER)= $Y_a/S_a+Y_b/S_b$, Where Y_A and Y_B are the individual crop yields in intercropping, and S_A and S_B are their yields as sole crops. Production efficiency (kg ha^{-1} day^{-1}) = LMEY (kg ha^{-1})/crop durations of the system. Where LMEY is little millet equivalent of inter and sequential crops.

2.5 Statistical analysis

The data collected were statistically analysed and subjected to Analysis of Variance (ANOVA) using SAS University edition, USA. The differences between the treatment means were tested for their statistical significance with an appropriate critical difference (CD) value of $p<0.05$ (Gomez and Gomez 1984).

3. RESULTS

3.1 Crop growth and yield attributes of first crops

3.1.1 Cereal component - little millet

Intercropping of redgram at different ratios with little millet notably influenced the crop development and yield attributes of the latter. During initial crop growth, a ratio of 6:2 (little millet: redgram) produced the tallest plants (90.2 cm), which was statistically comparable with the 4:1 and 8:2 combinations (Table 3). The same combination of 6 rows of little millet and one row of redgram produced a greater number of productive tillers (9.2 nos.) and SPAD value (41.9). However, this trend did not reflect in the days to 50% flowering, as all the ratios responded equally. The heavier panicles and test weight were noted in the 4:1 combination compared to the 8:2 combinations. The combination of little millet and red gram in a 4:1 ratio yielded the highest average panicle weight at 5.4 grams. While other ratios also demonstrated an increase in panicle weight, their results were similar, showing no significant difference in panicle weight gain among them. In contrast to the above, test weight was higher under the 6:2 combination. The 4:1 ratio (little millet and redgram) yielded 511 kg ha^{-1} of little millet grains, and this was closely followed by the 6:2 combination. The lowest grain yield of 451 kg ha^{-1} was registered in 8:2 ratios (Table 3). Accumulation of dry matter is an important parameter that influences yield. The DMP showed a similar trend as that of grain yield. A higher mean DMP (1632 kg ha^{-1}) was recorded under the 4:1 combination, which was 13 & 20 % higher than the 6:2 and 8:2 combinations.

3.1.2 Legume component Intercrop redgram

The population of intercrop is an essential factor that influences the yield and income of rainfed farmers. The 4:1 ratio accommodated a higher redgram population (10379 nos) which were 107 & 545 numbers greater compared to the 6:2 and 8:2 combinations. The different ratios of redgram intercrop did not show variation in plant height. The redgram data showed that the 4:1 combination had a greater Leaf Area Index (LAI) of 1.9, more pods (74.1), higher DMP of 113 kg ha^{-1} and a seed yield of 67 kg ha^{-1} compared to the 8:2 combination. The 6:2 combination showed similar results to the 4:1 combination in terms of LAI, number of pods and seed yield (Figure 2).

The land equivalent ratio (LER) is an indicator of effective land utilization under different crop combinations. The calculated little millet equivalent yield for redgram was also higher in the same combination (Table 4). Adopting the 4:1 little millet and redgram combination among the different combinations recorded a higher LER of 1.2 followed by 6:2 (1.1), whereas 8:2 combinations had a lesser LER (1.0). Production efficiency and land-use efficiency (LUE) are useful indicators to ascertain the synergisms among crops in the cropping system for judicious utilization of natural resources. Adoption of a 4:1 ratio of little millet and redgram produced greater LMEY (730 kg ha^{-1}) and production efficiency (4.5 kg ha^{-1}day^{-1}) followed by a 6:2 combination (Table 3). However, LUE was not significant in different ratios of little millet and redgram.

3.1.3 Legume component – Sequential crop moth bean, horse gram and blackgram

Three crops viz., moth bean, horse gram and blackgram were raised as sequential crops after the harvest of little millet, to increase soil fertility and profit of the rainfed farmers. Different combinations of little millet and redgram considerably influenced the seed yield of the sequential crop. The prime factor of the variations in population counts of the preceding crops had influenced the yield of sequential crops. The 4:1 ratio (little millet: redgram) recorded higher seed and DMP of horse gram (90 &150 kg ha^{-1}), black gram (48 &110 kg ha^{-1}) and moth bean (72&119 kg ha^{-1}) followed by 6:2 and 8:2 combination. Among the sequential crops, horse gram performed better and produced greater seed yield (78 kg ha^{-1}) and DMP (128 kg ha^{-1}) followed by moth bean compared to blackgram (Figure 3).

The efficiency of better utilization of land and other resources is reflected in production efficiency and land-use efficiency (LUE). Among the sequential crops, horse gram recorded higher LMEY (787 kg ha^{-1}) and land-use efficiency (47.9%) compared to other pulses.

3.2 Soil fertility and nutrient utility

Soil nutrients are the most important growth factor for improving crop productivity in a rainfed environment. The results claimed that the growing of intercrop increased soil fertility and nutrient availability as depicted in Table 5. The 4:1 combination of little millet and redgram with horse gram sequence recorded greater SOC (4.3 g kg^{-1}), augmenting 13.5% organic carbon compared to the time zero value, which was statistically comparable ($p<0.05$) with the 6:2 combination. Across the system, little millet and redgram (4: 1) with sequential horse gram increased 8.1% of organic carbon compared to little millet and redgram (8:2). The post-harvest soil available nitrogen (SAN) status also showed a similar trend of SOC. The 4:1 combination recorded higher SAN (157 kg ha^{-1}) compared to the 6:2 and 8:2 combination. The system little millet and redgram (4:1) with horse gram sequence registered greater SAN of 159 kg ha^{-1} compared to the 8:2 combination with blackgram sequence (148 kg ha-1). Phosphorus is crucial for the growth of roots and seeds in crops. When pulses are introduced in the crop mixer, they tend to deplete the soil available phosphorus more in the 4:1 combination of little millet and red gram (28.9 kg ha^{-1}) than in the 8:2 combination (31.3 kg ha^{-1}). The sequential crop did not show variation in SAP across the various combinations of little millet and redgram intercrop. The soil available potassium also runs down under the 4:1 combination (170 kg ha^{-1}) compared to the 6:2 combination (174 kg ha^{-1}).

Nutrient assimilation is essential to regulate physiological activity and crop development. The N uptake was greater under the 4:1 combination (43.1kg ha^{-1}) followed by the 6:2 and 8:2 combinations. Among the crops, a major part of N was utilized by little millet, horse gram, and moth bean under the 4:1 combination (Table 4). The P and K utilization was greater under the 4:1 combination (9.7 & 37.6 kg ha^{-1}), which was statistically ($p<0.05$) comparable with the 6:2 combination. The lowest P and K uptake was seen under the 8:2 combinations (Table 5). Among the crops, little millet and redgram utilized a greater P of 72 per cent in the total uptake than sequential pulse crops. The main crop, little millet utilised a substantial quantity of K (23.9 kg ha^{-1}), resulting in greater K uptake in the 4:1 combination. The results revealed that little millet utilized more N and K than pulse crops, whereas phosphorous was equally utilized by little millet and pulse crops, with a slight edge over little millet. The nutrient balance sheet of the cropping system indicated that a positive balance of soil available nitrogen was noticed in the 4:1 (little millet: redgram) combination with pulses sequence followed by 6:2 and 8:2 combinations (Figure 4). The greater soil nitrogen built-up of 13 kg ha^{-1} was recorded under the 4:1 combination of little millet + redgram and black gram sequence as against 8:2 combinations (2 kg ha^{-1}). In contrast to nitrogen, phosphorous depletion was noted in the 4:1 little millet + redgram and pulses sequence. The other little millet + redgram combinations showed positive soil phosphorous balance. The soil available potassium depletion was noticed in all the treatments. The greater negative balance of soil potassium was registered in the 4:1 combination with horse gram and moth bean sequence (-8 kg ha^{-1}) followed by the 8:2 combination. The least soil potassium depletion was noticed at 6:2 little millet + redgram and black gram sequence (-2 kg ha^{-1}), depletion was comparatively 6 kg less than the 4:1 combination of little millet and redgram with horse gram sequence.

4. DISCUSSION

The success of legume-cereal mixtures in rainfed areas depends on soil type and moisture. Fertile soils support most plant species well, while mixtures can also thrive on poor soils. Due to the different growth patterns of crop components, plants can effectively utilize habitat conditions even in less favourable or rain-dependent poor soil conditions.

4.1 Crop growth and yield attributes

The plant population, growth, physiological and yield attributes are important driving forces that reflect the photosynthetic activity and yield of rainfed crops. The plant population tends to show a declining trend over the years by 43%, for a 4:1 ratio. However, the population reduction was more pronounced in the 8:2 ratio, reaching 63%. In rain-dependent agriculture, the timing and duration of rainfall during the cropping seasons can have a significant impact. Rainfall is the primary factor resulting in the reduction of plant population. In 2016, the amount of rainfall received was 217 mm over 17 rainy days, whereas in 2018, it decreased significantly to only 124 mm across just 7 days. During the crop period, rainfall was insufficient or untimely, it created severe moisture stress and affected the growth and yield of little millet. Maintaining an optimal population is crucial for achieving maximum yields, which was completely compromised in this situation. The greater number of productive tillers and SPAD values under the 6:2 and 4:1 combination of little millet and redgram were seemingly ascribed to red gram-mediated microclimate, which altered leaf temperature and higher nitrogen availability (Entz et al., 2002). The yield increase under the 4:1 combination was meagrely (3 & 12 %) superior to the 6:2 and 8:2 combinations. The mean little millet yield was poor, owing to low rainfall in the crop-growing seasons of 2016 and 2017 (124 and 193 mm, respectively), as well as fewer rainy days in 2016 (7 days). The higher panicle weight and seed yield in the 4:1 combination could be attributed to higher soil nitrogen availability, as suggested by Layek et al. (2014) and the favourable microclimate provided by red gram. (Meena et al., 2015).. The greater DMP under the 4:1 combination is mainly attributed to a higher leaf area, as evidenced by the study. The findings revealed that intercropped redgram created a favourable microclimate and increased soil nitrogen availability via biological N-fixation by root nodules (Santi et al., 2013). These might have helped in better photo-synthetase production and assimilation in little millet. Further higher nitrogen utility also contributed to higher DMP (Senaratne et al., 1993).

The intercropping of redgram in millet crop has multifaceted benefits to the main crop and yield advantage over monocropping. The high LAI of redgram might be due to optimum spatial planting and judicious resource availability in the deep layer resulting in higher photo interaction, better soil nutrient availability and utility (Ghanbari et al., 2010), efficient utilization of water and light, and lesser competition with the main crop (Zhang et al., 2011). More number of pods, higher seed yield, and DMP of redgram in the 4:1 combination mainly due to the better establishment and nutrient availability. The optimum population of intercrop, i.e., redgram, ensured less competition for space and nutrients with little millet, which facilitated better growth and seed yield. Increasing the population of pulse crops enhances the yield of millet, as evident from the study. It is clearly due to the contribution of red gram in fixing atmospheric nitrogen into the soil, which has been utilized by the little millet. The additional benefits of growing millet-pulse mixtures are their effect on soil fertility and their phytosanitary status. The positive correlation between the density of red gram and little millet yield was noticed. Mixing pulses with millets is useful in many ways. It makes better utilization of habitat resources than sole crops. Differentiation in the type and depth of the root systems of millets and pulses allows them to use nutrients from different soil layers, the result of which is a compensatory growth and development of plants.

The higher LER in the 4:1 combination indicated that the main and intercrop efficiently utilized the resources and resulted in better assimilation with a greater yield advantage than the 8:2 combination (Caballero et al., 1995). During the cropping seasons of 2016, 2017, and 2018, the average yield of all sequential crops was significantly low across all combinations. This decline in yield was primarily attributed to inadequate rainfall, with recorded amounts of 20mm, 65mm, and 78mm respectively, coupled with fewer wet days (3, 5, and 7 days) throughout the cropping periods. The higher seed yield under horse gram could be mainly due to its hardening and moisture stress tolerance nature (Prasad and Singh, 2015). Besides, it is capable of utilizing dew moisture and regulating the physiological activity, which positively regulates the source-sink relationship and increases seed yield (Jyoti and Yadav, 2012). Further, the optimum crop geometry of the 4:1 ratio for intercropping created a favourable microclimate for sequential crops, which helped produce greater yield than the other combinations (Maitra et al., 2021). Redgram-mediated microclimate and soil fertility improvement favour greater LMEY and production efficiency in the 4:1 combination. Moisture stress tolerant capacity and 100 days duration of horse gram helped to augment biomass production, resulting in higher LMEY and LUE (Nadeem et al., 2019).

Considering three years of cropping, the growth attributes of little millet tend to show a declining trend (2016-2018) for plant growth and SPAD values. Nevertheless, the physiological parameters like LAI and days to 50% flowering showed an increasing trend. With regards to yield and yield parameters like panicle weight, test weight and yield also showed a decreasing trend over the years (Table 3). However, the influence of years of cultivation on the growth and performance of red gram was different as the parameters like plant height, LAI, and number of pods per plant showed an initial decline and later increased. However, the yield of red gram progressively declined over the years.

4.2 Soil fertility and nutrient utility

Soil fertility is an important production factor, playing a multi-functional role in crop production by providing balanced nutrition to the crop. The inclusion of pulses creates a favourable soil environment for better crop production (Gan et al., 2015). The quantity of organic matter present in the soil is the net difference between organic biomass input and losses. The extent and course that inter and sequential cropping affects soil organic matter, typically measured via SOC, is thus a function of how it impacts these inputs and losses. The greater SOC content under little millet + redgram (4:1) with horse gram and moth bean is mainly attributed to the greater below-ground biomass (little millet 850 kg ha^{-1}) leaf litter addition from redgram (250 kg ha^{-1}), horse gram (50 kg ha^{-1}), and moth bean (30 kg ha^{-1}). Further, the decomposition of finer roots of redgram (380 kg ha^{-1}) and sequence crops also contributed to elevated SOC (Ganeshamurthy et al., 2006).

The improvement in SOC content in the present systems has influenced soil nutrient availability and also plant acquisition. Intercropping redgram in little millet at a ratio of 4:1 showed greater SAN, which could be mainly ascribed to the nitrogen addition through biological N fixation of legumes, as supported by (Li et al., 2009; Mhango et al., 2017). Furthermore, presumably, leaf litter addition by redgram and horse gram might have helped to build up soil organic matter (Rao and Gill, 1995) and thereby favoured an increase in nitrogen built-up in the studied soil (Rao and Balachandar, 2017). In contrast to SAN, the exhaustion of SAP and SAK was noticed under the same combination, which is mainly attributed to greater uptake of P and K by little millet, redgram and sequential crops (Mugwe et al., 2011). Presumably, redgram utilized a tangible quantum (3.3 kg ha^{-1}) of phosphorous (Adjei-Nsiah et al., 2018) along with little millet (3.7 kg ha^{-1}) as evidenced by this study result, which was consonance with the findings of Wafula et al. (2018) in ragi. In SAK, little millet + redgram and horse gram and little millet + redgram and black gram sequence consumed more soil potassium and depleted its availability.

As in many instances, increases in the quantity of nutrients stored in the soil will lead to greater plant nutrient availability. A greater little millet population favoured higher uptake of N and a significant quantity of N from the soil might be used for crop growth and development (Chalka and Nepalia, 2006). The greater P uptake under the 4:1 combination is mainly ascribed to a higher accumulation of P in little millet (3.7 kg ha^{-1}) and redgram (3.2 kg ha^{-1}), which is the possible reason for phosphorous depletion under the 4:1 combination than in other combinations (Li et al., 2007). The greater potassium intake of little millet is attributed to the negative balance of potassium in all the treatments (Ashraf et al., 2002). Nutrient balance results necessitate advocating the additional phosphorous and potassium fertilization for the little millet-pulse cropping system under the rainfed semiarid tropics.

5. CONCLUSIONS

Adoption of intercropping redgram with little millet at a 4:1 ratio (one row of redgram after every four rows of little millet) and horse gram as a sequential crop in a rain-dependent alfisol resulted in higher (18%) little millet equivalent yield, production efficiency (18.4%) and land-use efficiency (4.5%), reducing the negative effects of climate vulnerability in semi-arid. In addition, the same crop mixes positively built-up soil available nitrogen and depleted the soil phosphorous and potassium in the little millet-pulse system. Moreover, the study findings underscore the importance of incorporating pulses as inter and sequential crops, as they are crucial components for enhancing yield and nitrogen balance. To rectify the imbalanced levels of phosphorus (P) and potassium (K) within the crop mix, it is imperative to revisit research on optimizing phosphorus and potassium fertilization across various soil types. This research is vital for boosting little millet and pulse productivity, improving farm economics, and maintaining sustainable soil fertility in Alfisol under rainfed little millet-pulse cropping systems.

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Table 1. Initial soil physicochemical properties (0-15 cm depth; Mean of three-year initial soil samples analytical data and data in parenthesis is the standard error of three years).

Available Nutrients	kg ha^{-1}	Physico-chemical properties	
Nitrogen	146 (±2.8)	pH	5.7 (±0.03)
Phosphorus	30 (±1.2)	EC (dS m^{-1})	0.11 (±0.01)
Potassium	178 (±3.0)	Organic C (g kg^{-1})	3.8 (±0.17)
Sulphur (mg kg^{-1})	8.4 (±0.7)	Bulk density (Mg m^{-3})	1.40 (±0.005)
Exchangeable Ca (meq 100 g^{-1})	1.8 (±0.1)	Pore space (%)	41.9 (±2.0)

Table 2. Experimental details.

Year	Date of sowing of main crop and intercrop	Date of harvest of main crop-millet	Date of harvest of intercrop-red gram	Rain fall (mm)	Rainy days (Nos)
2016	18.11.2016	16.02.2017	27.03.2017	124	7
2017	21.8.2017	4.12.2017	12.02.2018	193	15
2018	20.8.2018	13.11.2018	4.02.2019	217	17

Table 3. Effect of cereal / legume mixtures on biometric and yield attributes of little millet.

Treatment	Plant Height (cm)	No. of productive tillers	Days to 50% flowering	SPAD value	Leaf area (cm^2 $Plant^{-1}$)	Panicle length (cm)	Panicle weight (g)	Test weight (g)	Seed yield (kg ha^{-1})	DMP (kg ha^{-1})
Little millet +Redgram (4:1)	90.1	8.9	60.1	42.6	271	25.4	5.4	2.4	511	1658
Little millet +Redgram (6:2)	90.2	9.1	60.7	41.9	297	24.9	5.4	2.6	497	1592
Little millet +Redgram (8:2)	82.7	8.3	61.3	40.9	313	24.1	5.1	2.4	451	1557
Sole little millet	80.1	8.4	60.5	39.2	275	23.1	4.9	2.3	523	1789
CD ($P \leq 0.05$)	5.9	1.7	NS	1.7	5.4	2.1	1.7	0.3	53	122
DMP-Dry matter production, CD-Critical difference value from ANOVA										

Table 4. Effect of cereal/legume mixtures on LMEY, LER, PE and LUE.

Treatment	LMEY (kg ha^{-1})	LER	PE (kg ha^{-1} day^{-1})	LUE (%)
T1- Little millet +Redgram (4:1)	730	1.2	4.5	46.3
T 2-Little millet +Redgram (6:2)	696	1.1	4.3	44.3
T3- Little millet +Redgram (8:2)	618	1.0	3.8	45.3
LMEY- Little millet equivalent yield, LER-Land equivalent ratio, PE- Production efficiency, LUE-Land Use Efficiency				

Table 5. Effect of cereal/legume mixtures on soil available nutrients and crop nutrient acquisition.

Treatment	Organic carbon (g kg^{-1})	Soil available nutrients (kg ha^{-1})			Nutrient uptake (kg ha^{-1})		
		N	P	K	N	P	K
Little millet +Redgram (4:1)	4.1	157.3	28.9	170.7	43.1	9.7	37.6
Little millet +Redgram (6:2)	3.9	153.3	30.6	174.3	40.5	8.6	36
Little millet +Redgram (8:2)	3.9	149.3	31.3	172.0	39.3	7.6	34.6
Sole little millet	3.9	147.5	29.3	164.8	31.5	7.1	30.9
CD ($P \leq 0.05$)	0.3	9.0	1.5	NS	3.7	0.8	NS
N-Nitrogen, P-Phosphorus, K-Potassium							

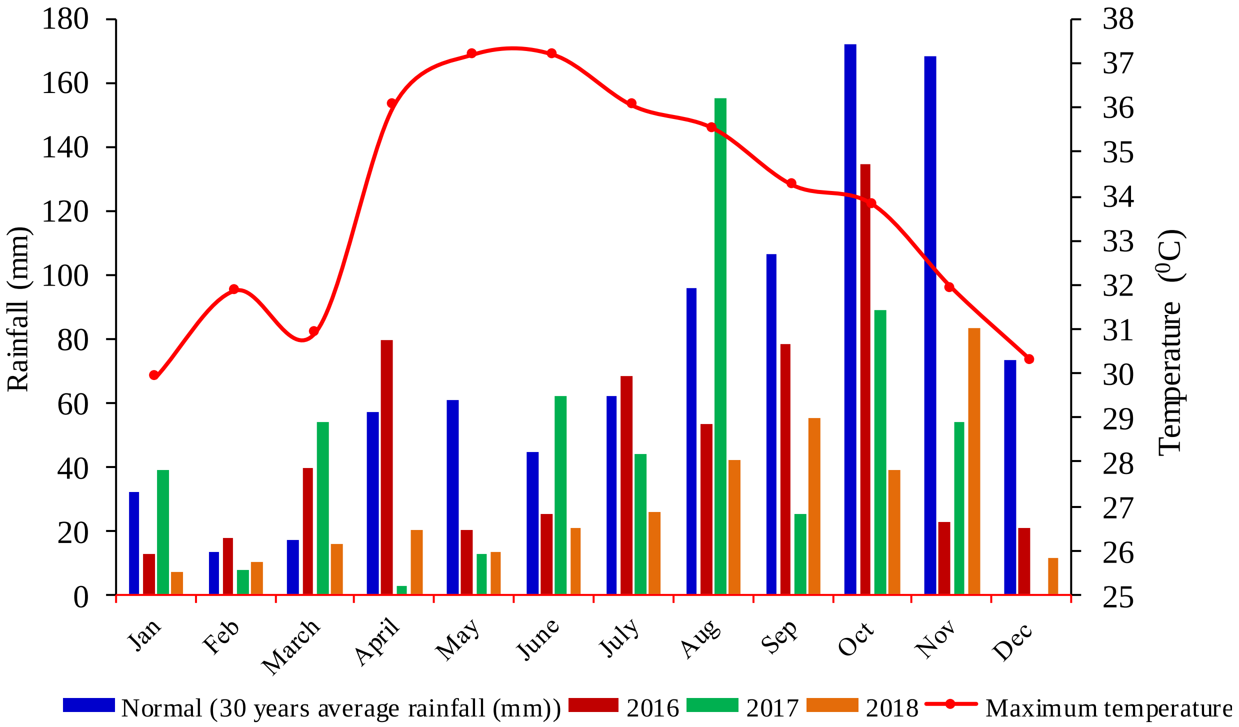

Figure 1. Weekly rainfall and maximum temperature for the little millet and sequential crops growing seasons of 2016-2018 (Three years of rainfall data compared with 30 years mean weekly rainfall data and maximum temperature curve is mean for the 3 years of the experiment).

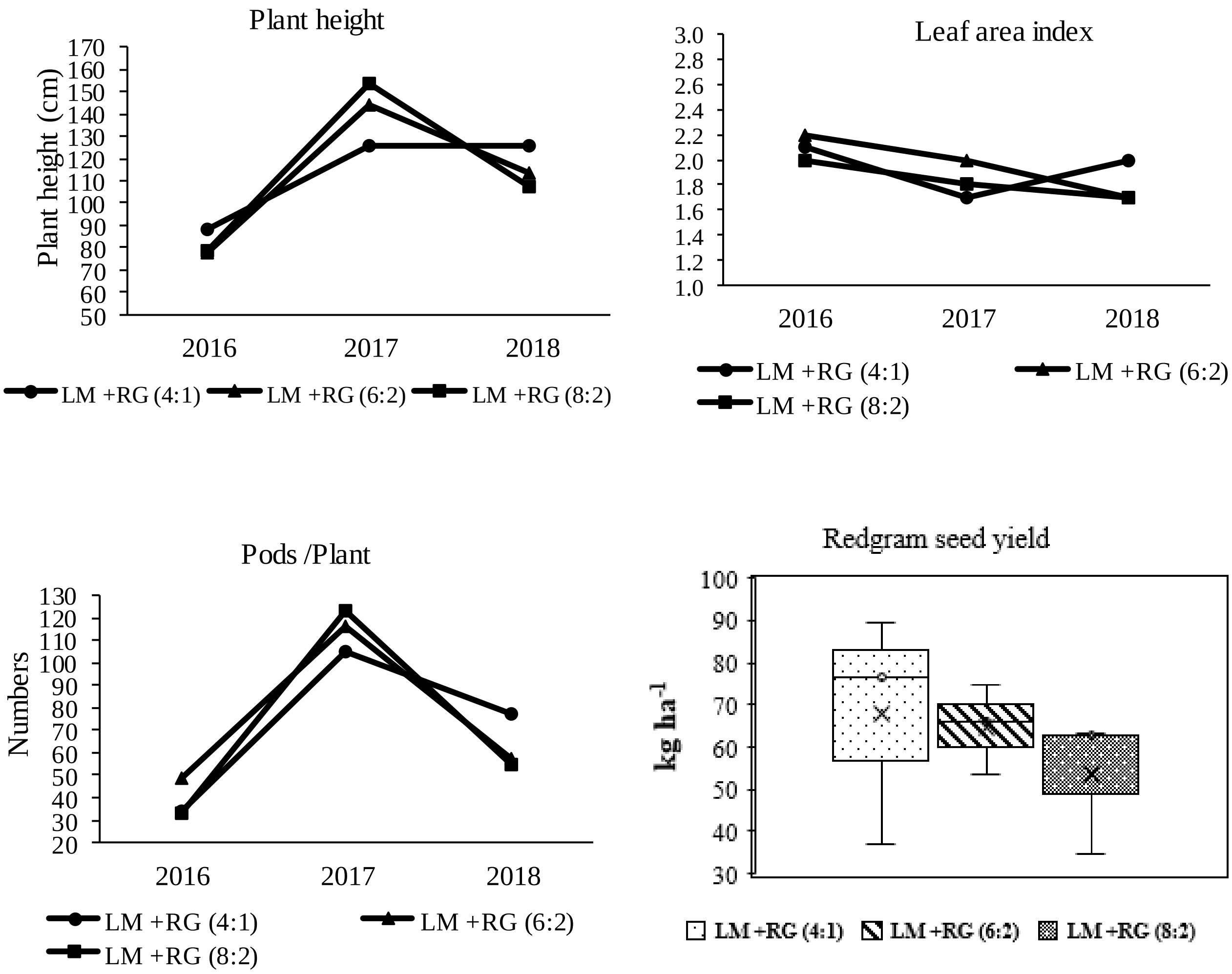

Figure 2. Effect of cereal/legume mixtures on biometric and yield attributes: (a) Plant height, (b) Leaf area index, (c) Number of pods, and (d) Seed yield of redgram.

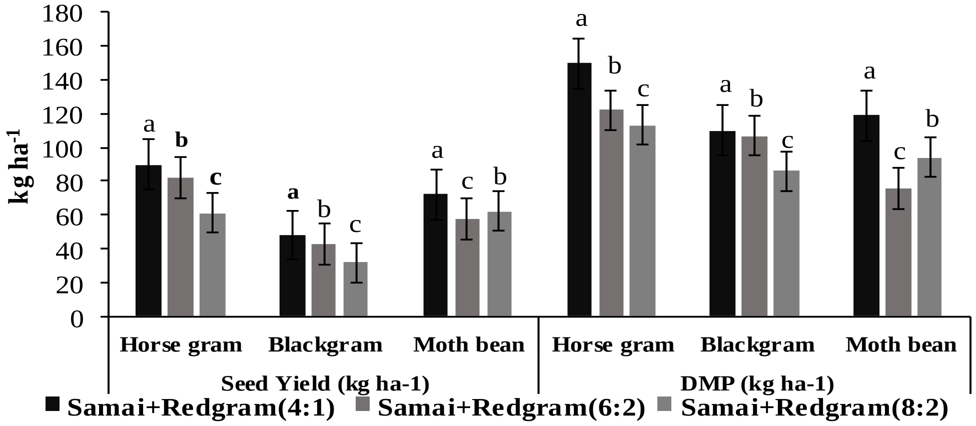

Figure 3. Effect of different combination little millet and redgram intercrop on seed yield and dry matter production of sequential pulse crops.

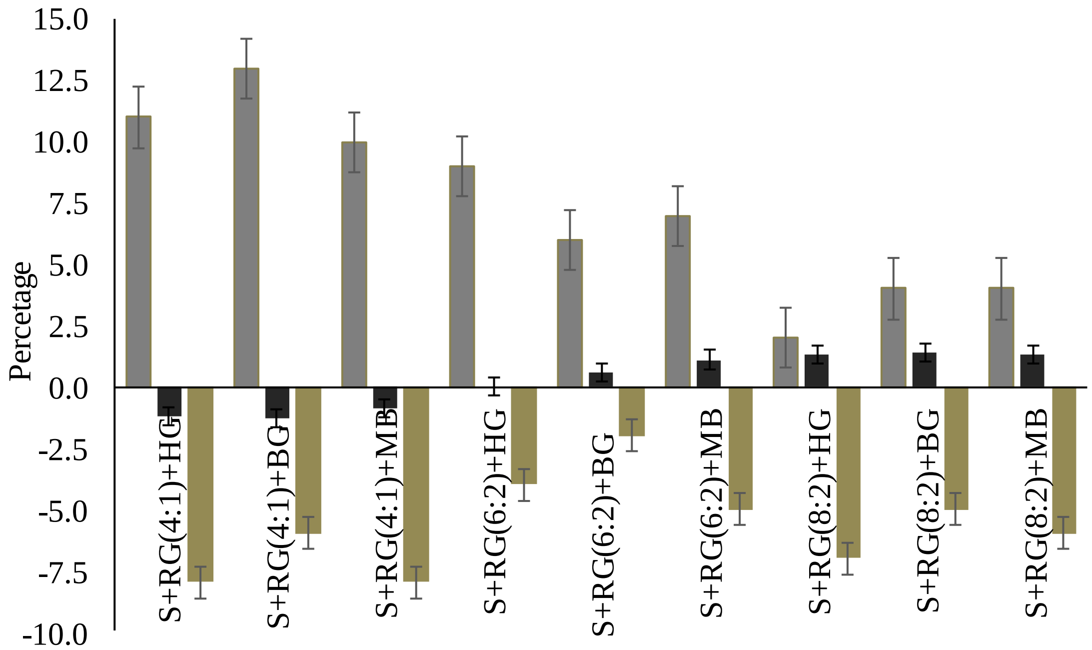

Figure 4. Effects of cereal/legume mixtures on soil available nitrogen, phosphorus and potassium balance in Alfisol under rainfed condition.