

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

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**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<sup>-1</sup>) and straw yield (1632 kg ha<sup>-1</sup>) of little millet. Similarly, little millet grain equivalent yield and production efficiency were also higher (730 kg ha<sup>-1</sup> & 4.5 kg ha<sup>-1</sup> day<sup>-1</sup>) in the 4:1 combination with sequential horse gram. Regarding soil fertility, a 4:1 combination with sequential horse gram resulted in significant nitrogen build-up (157.3 kg ha<sup>-1</sup>) and phosphorus (9.7 kg ha<sup>-1</sup>) and potassium uptake (37.6 kg ha<sup>-1</sup>). 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.

41 **1. INTRODUCTION**

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

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

74 Millets are vital for low-income farmers in hot, dry regions of Africa and Asia, where over  
75 97% of millet production and consumption occurs (McDonough et al., 2000). Millets are  
76 small-seeded grasses widely grown across the world as cereal crops or grains for fodder and  
77 human food. Various types of millet crops, such as sorghum (*Sorghum bicolor* (L.)), finger  
78 millet (*Eleusine coracana*), pearl millet (*Pennisetum glaucum*), barnyard millet (*Echinochloa*  
79 *colona*), kodo millet (*Paspalum scrobiculatum*), proso millet (*Panicum miliaceum*), and little  
80 millet (*Panicum miliare*), are grown across the globe. Nutri millets are traditional cereal  
81 crops, which are grown in arid and semi-arid zones as rainfed crops, under marginal and  
82 submarginal conditions of soil fertility and moisture. However, it's crucial to recognize that  
83 despite these difficulties, the average grain yield remains impressively high, nearly reaching  
84 1000 kg per hectare. Recognizing this, there's a growing awareness of the need for increased  
85 research and development for these crops. According to FAOSTAT (2018), there has been a  
86 decline of 25.7% in the global area under millet cultivation from 1961 to 2018, and the largest  
87 area reduction was observed in Asia, whereas the lowest was observed in Africa. Little millet,  
88 a hardy crop with a short life, is grown entirely in rainfed conditions (Vetriventhan et al.,  
89 2020), with a production capacity of 1600 kg ha<sup>-1</sup>, but farmers only obtain 750 kg ha<sup>-1</sup> due to  
90 erratic monsoon rains and a lack of adoption of improved soil and crop production  
91 technologies (Tadele, 2016).

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

106 suitable sequential crop for improving system productivity and soil fertility under rainfed  
107 conditions.

108

## 109 **2. MATERIALS AND METHODS**

### 110 **2.1 Site description and weather conditions**

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

118

### 119 **2.2 Experimental design**

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

### 137 **2.3 Soil and plant analysis**

138 Soil samples were collected, before seeding, at 15 cm soil depth and soil physicochemical  
139 properties were analyzed and presented in Table 1. Each year, after harvesting the crops, four

140 soil samples were taken from each plot at a depth of 0-15 cm using an auger. The collected  
141 soil samples were mixed well and representative single representative composite soil sample  
142 was prepared for each plot. Composite soil samples were air-dried, ground and passed  
143 through a 2.0 mm sieve and used for soil physicochemical analysis.

144 Soil organic carbon content was analyzed by the Walkley-Black method (Walkley and  
145 Black, 1934). Soil available nitrogen (SAN) was estimated by the alkaline potassium  
146 permanganate method (Subbiah and Asija, 1956) in which 10 g of soil was treated with an  
147 excess of 0.32 % alkaline permanganate and distilled in the presence of 2.5% NaOH. Soil  
148 available phosphorous (SAP) was measured by the Bray and Kurtz No. 1 method (Olsen and  
149 Sommers, 1982). An extract was prepared from 5 g of soil and reacted with Bray 1 reagent  
150 (0.03 N NH<sub>4</sub>F and 0.02 N HCl). The blue color was developed by the ascorbic method and its  
151 intensity was measured at 660 nm in a UV-VIS Spectrophotometer (Jetways 6203 model).  
152 Soil available potassium was estimated by the ammonium acetate method (Knudsen et al.,  
153 1983). The total N content in plant and seed samples was analyzed using an automated  
154 Kjeldplus N analyzer (Bremner and Mulvaney, 1982); total P content was analyzed by  
155 developing Barton's yellow colour, assessed using Jetways 6203 UV spectroscopy (Olsen and  
156 Sommers, 1982) and total K content was quantified using a flame photometer. The acquisition  
157 of nitrogen (N), phosphorus (P), and potassium (K) was calculated by multiplying the  
158 concentrations of N, P, and K by the straw and grain yields of the respective crops. The  
159 nutrient balance was calculated by subtracting the post-harvest soil nutrient status from the  
160 initial soil nutrient status of the experimental plots.

161

#### 162 **2.4 Crop data collection**

163 Five plants were randomly selected and tagged in each plot for crop growth and yield  
164 characteristics like plant height, the number of productive tillers, SPAD value, leaf area and  
165 days to 50% flowering, test weight, panicle length and panicle weight were measured during  
166 the peak vegetative and maturity stages of little millet. The growth and yield parameters of  
167 redgram and sequential pulse crops were recorded at flowering and harvest. The chlorophyll  
168 content was measured at the peak vegetative stage (45 Days after sowing) in fully opened 4th  
169 and 3rd leaf from the top from 10.30 am to 12.30 pm using a Minolta Model 502 SPAD  
170 Meter. Seed yield and dry matter production (whole plant dry weight) were recorded from 20  
171 m<sup>2</sup> (5 m × 4 m) plots. Seeds were sun-dried and weighed at 10 % moisture. For dry matter  
172 production assessment, 10 plants selected were dried in a hot air oven and weighed, and tissue  
173 moisture content was corrected for the entire plot plant weight.

174 The little millet equivalent yield (LMEY) of the intercropping system was calculated by  
175 considering the seed yield of component crops and the prevailing market price of both millet  
176 and pulse crops by using the following formulas (Lal et al., 2017). The land equivalent ratio  
177 was calculated by dividing the intercropped yield by sole crops yield (Mead and Willey,  
178 1980), Land use efficiency (LUE) was worked out by dividing the total duration of crops in a  
179 cropping system by the total day in the year (365 days) outlined by Jamwal (2001). The  
180 production efficiency (PE) was assessed by dividing the mean yield of sole crops by the mean  
181 yield of crops in the mixtures (Agegnehu et al., 2006).

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

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

189

## 190 **2.5 Statistical analysis**

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

195

## 196 **3. RESULTS**

### 197 **3.1 Crop growth and yield attributes of first crops**

#### 198 **3.1.1 Cereal component - little millet**

199 Intercropping of redgram at different ratios with little millet notably influenced the crop  
200 development and yield attributes of the latter. During initial crop growth, a ratio of 6:2 (little  
201 millet: redgram) produced the tallest plants (90.2 cm), which was statistically comparable  
202 with the 4:1 and 8:2 combinations (Table 3). The same combination of 6 rows of little millet  
203 and one row of redgram produced a greater number of productive tillers (9.2 nos.) and SPAD  
204 value (41.9). However, this trend did not reflect in the days to 50% flowering, as all the ratios  
205 responded equally. The heavier panicles and test weight were noted in the 4:1 combination  
206 compared to the 8:2 combinations. The combination of little millet and red gram in a 4:1 ratio  
207 yielded the highest average panicle weight at 5.4 grams. While other ratios also demonstrated

208 an increase in panicle weight, their results were similar, showing no significant difference in  
209 panicle weight gain among them. In contrast to the above, test weight was higher under the  
210 6:2 combination. The 4:1 ratio (little millet and redgram) yielded 511 kg ha<sup>-1</sup> of little millet  
211 grains, and this was closely followed by the 6:2 combination. The lowest grain yield of 451  
212 kg ha<sup>-1</sup> was registered in 8:2 ratios (Table 3). Accumulation of dry matter is an important  
213 parameter that influences yield. The DMP showed a similar trend as that of grain yield. A  
214 higher mean DMP (1632 kg ha<sup>-1</sup>) was recorded under the 4:1 combination, which was 13 &  
215 20 % higher than the 6:2 and 8:2 combinations.

216

### 217 **3.1.2 Legume component Intercrop redgram**

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

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

236

### 237 **3.1.3 Legume component – Sequential crop moth bean, horse gram and blackgram**

238 Three crops viz., moth bean, horse gram and blackgram were raised as sequential crops after  
239 the harvest of little millet, to increase soil fertility and profit of the rainfed farmers. Different  
240 combinations of little millet and redgram considerably influenced the seed yield of the  
241 sequential crop. The prime factor of the variations in population counts of the preceding crops

242 had influenced the yield of sequential crops. The 4:1 ratio (little millet: redgram) recorded  
243 higher seed and DMP of horse gram (90 & 150 kg ha<sup>-1</sup>), black gram (48 & 110 kg ha<sup>-1</sup>) and  
244 moth bean (72 & 119 kg ha<sup>-1</sup>) followed by 6:2 and 8:2 combination. Among the sequential  
245 crops, horse gram performed better and produced greater seed yield (78 kg ha<sup>-1</sup>) and DMP  
246 (128 kg ha<sup>-1</sup>) followed by moth bean compared to blackgram (Figure 3).

247 The efficiency of better utilization of land and other resources is reflected in production  
248 efficiency and land-use efficiency (LUE). Among the sequential crops, horse gram recorded  
249 higher LMEY (787 kg ha<sup>-1</sup>) and land-use efficiency (47.9%) compared to other pulses.

250

### 251 **3.2 Soil fertility and nutrient utility**

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

269 Nutrient assimilation is essential to regulate physiological activity and crop development.  
270 The N uptake was greater under the 4:1 combination (43.1 kg ha<sup>-1</sup>) followed by the 6:2 and 8:2  
271 combinations. Among the crops, a major part of N was utilized by little millet, horse gram,  
272 and moth bean under the 4:1 combination (Table 4). The P and K utilization was greater  
273 under the 4:1 combination (9.7 & 37.6 kg ha<sup>-1</sup>), which was statistically (p<0.05) comparable  
274 with the 6:2 combination. The lowest P and K uptake was seen under the 8:2 combinations  
275 (Table 5). Among the crops, little millet and redgram utilized a greater P of 72 per cent in the



276 total uptake than sequential pulse crops. The main crop, little millet utilised a substantial  
277 quantity of K ( $23.9 \text{ kg ha}^{-1}$ ), resulting in greater K uptake in the 4:1 combination. The results  
278 revealed that little millet utilized more N and K than pulse crops, whereas phosphorous was  
279 equally utilized by little millet and pulse crops, with a slight edge over little millet. The  
280 nutrient balance sheet of the cropping system indicated that a positive balance of soil  
281 available nitrogen was noticed in the 4:1 (little millet: redgram) combination with pulses  
282 sequence followed by 6:2 and 8:2 combinations (Figure 4). The greater soil nitrogen built-up  
283 of  $13 \text{ kg ha}^{-1}$  was recorded under the 4:1 combination of little millet + redgram and black  
284 gram sequence as against 8:2 combinations ( $2 \text{ kg ha}^{-1}$ ). In contrast to nitrogen, phosphorous  
285 depletion was noted in the 4:1 little millet + redgram and pulses sequence. The other little  
286 millet + redgram combinations showed positive soil phosphorous balance. The soil available  
287 potassium depletion was noticed in all the treatments. The greater negative balance of soil  
288 potassium was registered in the 4:1 combination with horse gram and moth bean sequence ( $-8$   
289  $\text{kg ha}^{-1}$ ) followed by the 8:2 combination. The least soil potassium depletion was noticed at  
290 6:2 little millet + redgram and black gram sequence ( $-2 \text{ kg ha}^{-1}$ ), depletion was comparatively  
291  $6 \text{ kg}$  less than the 4:1 combination of little millet and redgram with horse gram sequence.

292

## 293 **4. DISCUSSION**

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

298

### 299 **4.1 Crop growth and yield attributes**

300 The plant population, growth, physiological and yield attributes are important driving forces  
301 that reflect the photosynthetic activity and yield of rainfed crops. The plant population tends  
302 to show a declining trend over the years by 43%, for a 4:1 ratio. However, the population  
303 reduction was more pronounced in the 8:2 ratio, reaching 63%. In rain-dependent agriculture,  
304 the timing and duration of rainfall during the cropping seasons can have a significant impact.  
305 Rainfall is the primary factor resulting in the reduction of plant population. In 2016, the  
306 amount of rainfall received was 217 mm over 17 rainy days, whereas in 2018, it decreased  
307 significantly to only 124 mm across just 7 days. During the crop period, rainfall was  
308 insufficient or untimely, it created severe moisture stress and affected the growth and yield of  
309 little millet. Maintaining an optimal population is crucial for achieving maximum yields,

310 which was completely compromised in this situation. The greater number of productive tillers  
311 and SPAD values under the 6:2 and 4:1 combination of little millet and redgram were  
312 seemingly ascribed to red gram-mediated microclimate, which altered leaf temperature and  
313 higher nitrogen availability (Entz et al., 2002). The yield increase under the 4:1 combination  
314 was meagrely (3 & 12 %) superior to the 6:2 and 8:2 combinations. The mean little millet  
315 yield was poor, owing to low rainfall in the crop-growing seasons of 2016 and 2017 (124 and  
316 193 mm, respectively), as well as fewer rainy days in 2016 (7 days). The higher panicle  
317 weight and seed yield in the 4:1 combination could be attributed to higher soil nitrogen  
318 availability, as suggested by Layek et al. (2014) and the favourable microclimate provided by  
319 red gram. (Meena et al., 2015).. The greater DMP under the 4:1 combination is mainly  
320 attributed to a higher leaf area, as evidenced by the study. The findings revealed that  
321 intercropped redgram created a favourable microclimate and increased soil nitrogen  
322 availability via biological N-fixation by root nodules (Santi et al., 2013). These might have  
323 helped in better photo-synthetase production and assimilation in little millet. Further higher  
324 nitrogen utility also contributed to higher DMP (Senaratne et al., 1993).

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

342 The higher LER in the 4:1 combination indicated that the main and intercrop efficiently  
343 utilized the resources and resulted in better assimilation with a greater yield advantage than  
344 the 8:2 combination (Caballero et al., 1995). During the cropping seasons of 2016, 2017, and  
345 2018, the average yield of all sequential crops was significantly low across all combinations.  
346 This decline in yield was primarily attributed to inadequate rainfall, with recorded amounts of  
347 20mm, 65mm, and 78mm respectively, coupled with fewer wet days (3, 5, and 7 days)  
348 throughout the cropping periods. The higher seed yield under horse gram could be mainly due  
349 to its hardening and moisture stress tolerance nature (Prasad and Singh, 2015). Besides, it is  
350 capable of utilizing dew moisture and regulating the physiological activity, which positively  
351 regulates the source-sink relationship and increases seed yield (Jyoti and Yadav, 2012).  
352 Further, the optimum crop geometry of the 4:1 ratio for intercropping created a favourable  
353 microclimate for sequential crops, which helped produce greater yield than the other  
354 combinations (Maitra et al., 2021). Redgram-mediated microclimate and soil fertility  
355 improvement favour greater LMEY and production efficiency in the 4:1 combination.  
356 Moisture stress tolerant capacity and 100 days duration of horse gram helped to augment  
357 biomass production, resulting in higher LMEY and LUE (Nadeem et al., 2019).

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

366

#### 367 **4.2 Soil fertility and nutrient utility**

368 Soil fertility is an important production factor, playing a multi-functional role in crop  
369 production by providing balanced nutrition to the crop. The inclusion of pulses creates a  
370 favourable soil environment for better crop production (Gan et al., 2015). The quantity of  
371 organic matter present in the soil is the net difference between organic biomass input and  
372 losses. The extent and course that inter and sequential cropping affects soil organic matter,  
373 typically measured via SOC, is thus a function of how it impacts these inputs and losses. The  
374 greater SOC content under little millet + redgram (4:1) with horse gram and moth bean is  
375 mainly attributed to the greater below-ground biomass (little millet 850 kg ha<sup>-1</sup>) leaf litter

376 addition from redgram (250 kg ha<sup>-1</sup>), horse gram (50 kg ha<sup>-1</sup>), and moth bean (30 kg ha<sup>-1</sup>).  
377 Further, the decomposition of finer roots of redgram (380 kg ha<sup>-1</sup>) and sequence crops also  
378 contributed to elevated SOC (Ganeshamurthy et al., 2006).

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

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

403

## 404 **5. CONCLUSIONS**

405 Adoption of intercropping redgram with little millet at a 4:1 ratio (one row of redgram after  
406 every four rows of little millet) and horse gram as a sequential crop in a rain-dependent alfisol  
407 resulted in higher (18%) little millet equivalent yield, production efficiency (18.4%) and land-  
408 use efficiency (4.5%), reducing the negative effects of climate vulnerability in semi-arid. In  
409 addition, the same crop mixes positively built-up soil available nitrogen and depleted the soil

410 phosphorous and potassium in the little millet-pulse system. Moreover, the study findings  
411 underscore the importance of incorporating pulses as inter and sequential crops, as they are  
412 crucial components for enhancing yield and nitrogen balance. To rectify the imbalanced levels  
413 of phosphorus (P) and potassium (K) within the crop mix, it is imperative to revisit research  
414 on optimizing phosphorus and potassium fertilization across various soil types. This research  
415 is vital for boosting little millet and pulse productivity, improving farm economics, and  
416 maintaining sustainable soil fertility in Alfisol under rainfed little millet-pulse cropping  
417 systems.

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

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

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**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

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**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 <sup>2</sup> Plant <sup>-1</sup> )	Panicle length (cm)	Panicle weight (g)	Test weight (g)	Seed yield (kg ha <sup>-1</sup> )	DMP (kg ha <sup>-1</sup> )
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≤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

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

Treatment	LMEY (kg ha <sup>-1</sup> )	LER	PE (kg ha <sup>-1</sup> day <sup>-1</sup> )	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

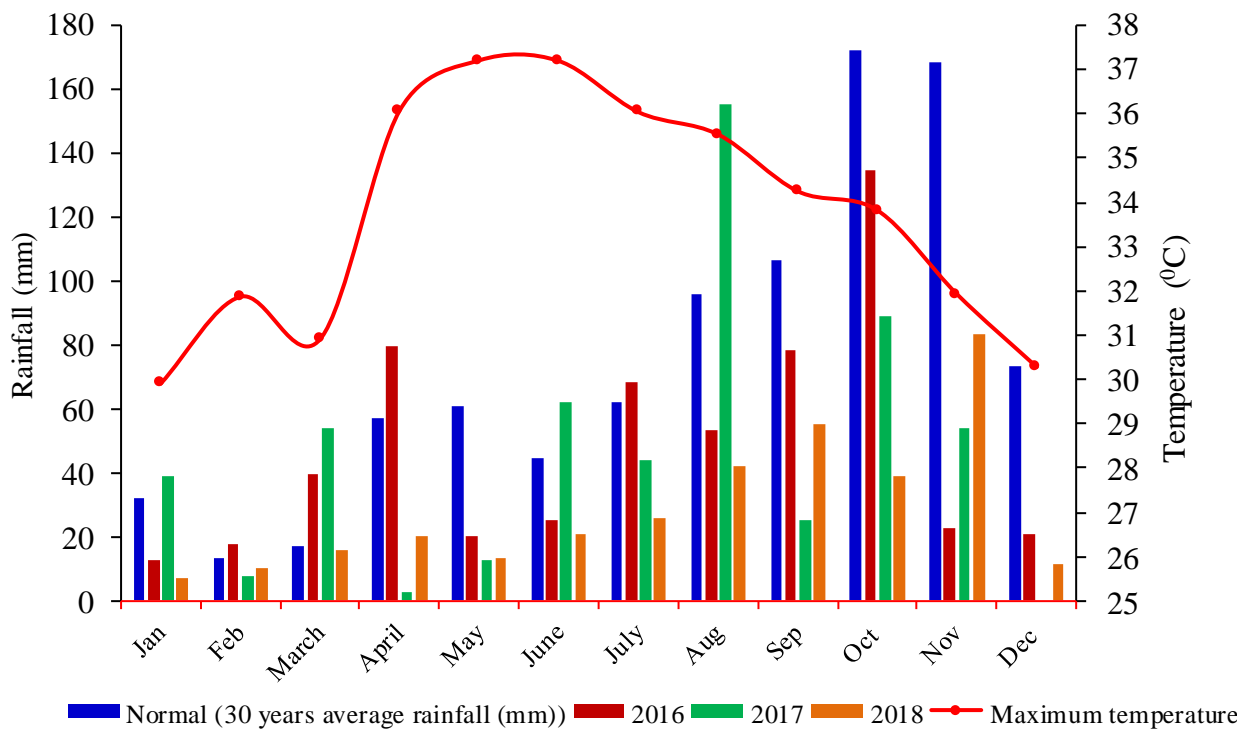
LMEY- Little millet equivalent yield, LER-Land equivalent ratio, PE- Production efficiency, LUE- Land Use Efficiency

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

Treatment	Organic carbon (g kg <sup>-1</sup> )	Soil available nutrients (kg ha <sup>-1</sup> )			Nutrient uptake (kg ha <sup>-1</sup> )		
		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≤0.05)	0.3	9.0	1.5	NS	3.7	0.8	NS

N-Nitrogen, P-Phosphorus, K-Potassium

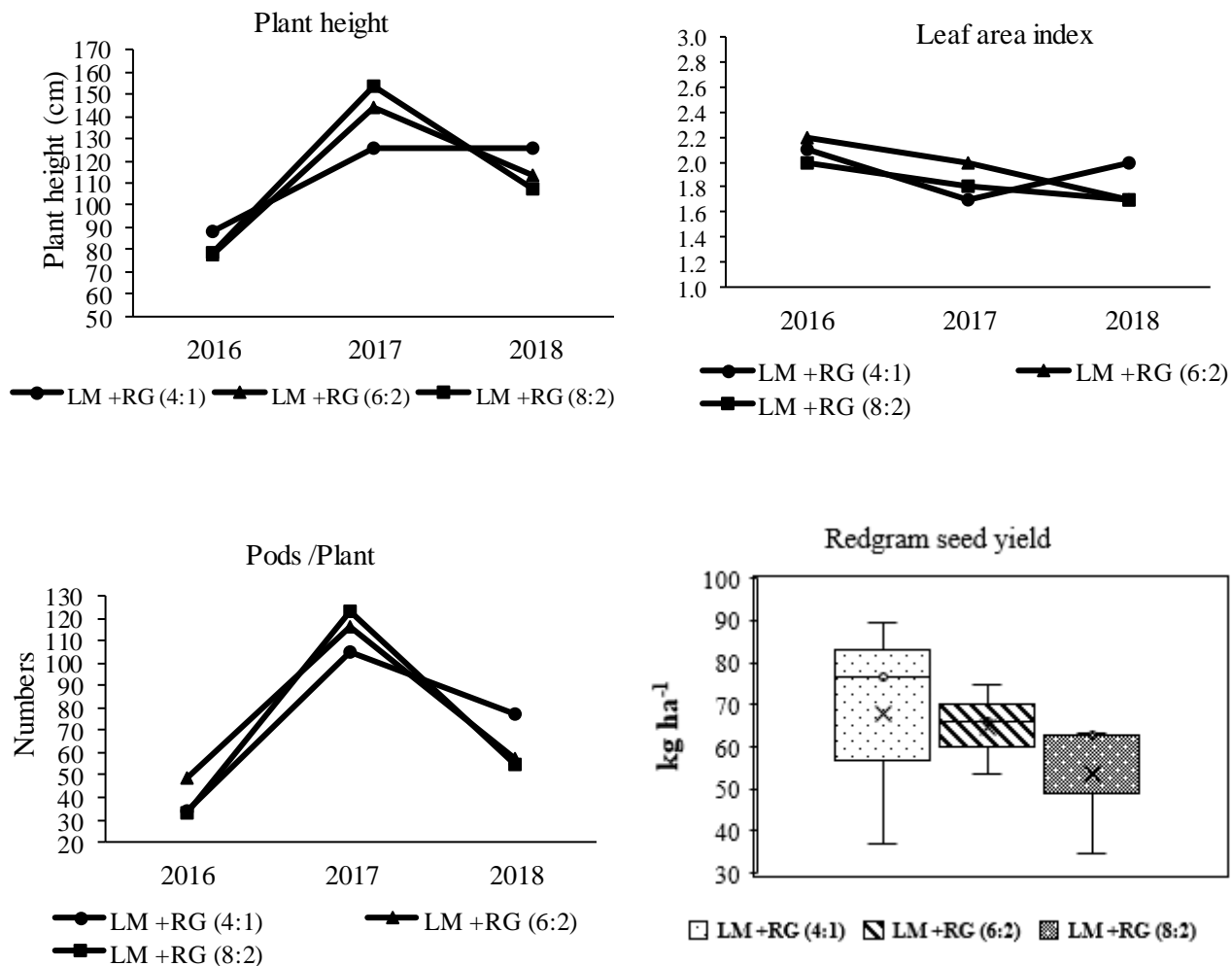


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580 **Figure 1.** Weekly rainfall and maximum temperature for the little millet and sequential crops growing  
 581 seasons of 2016-2018 (Three years of rainfall data compared with 30 years mean weekly rainfall data  
 582 and maximum temperature curve is mean for the 3 years of the experiment).  
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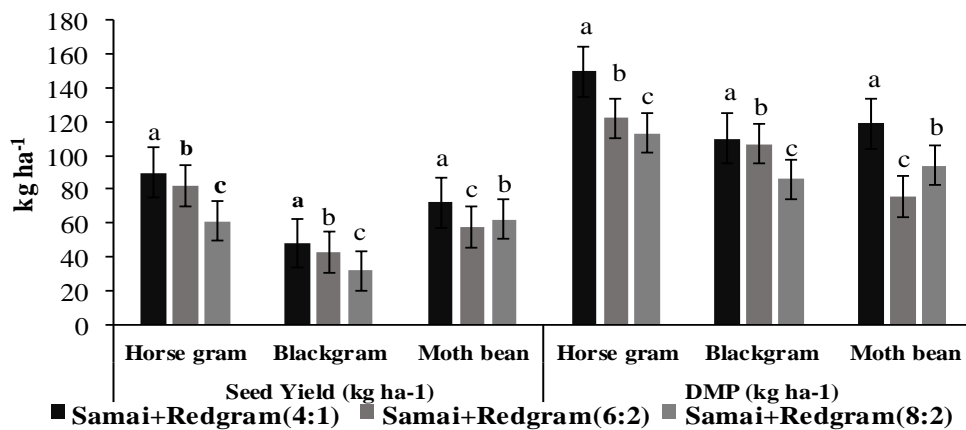
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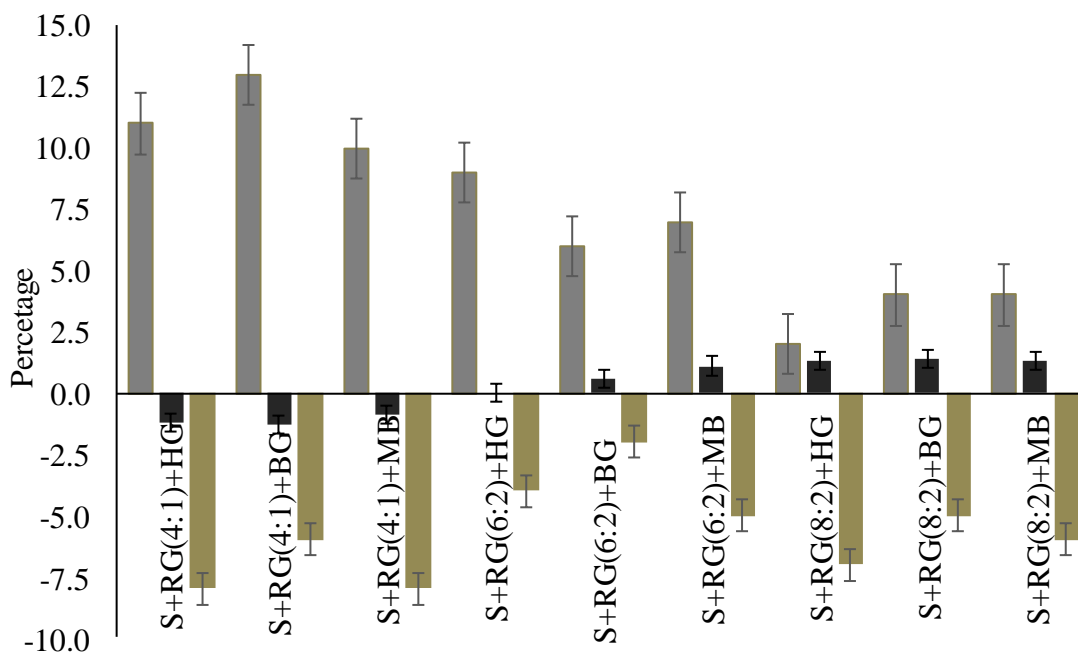
589 **Figure 2.** Effect of cereal/legume mixtures on biometric and yield attributes: (a) Plant height, (b) Leaf  
590 area index, (c) Number of pods, and (d) Seed yield of redgram.

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



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