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Row-ratio optimization and organic nutrient management in pearl millet + mungbean intercropping: yield, land-use efficiency and competitive interactions in the semi-arid zone of Rajasthan, India

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ABSTRACT

Cereal-legume intercropping with reduced dependence on external inputs is a promising option for the low-fertility soils of semi-arid Rajasthan. A field experiment was conducted during kharif 2023 on loamy sand soil at Jobner, Rajasthan, in a split-plot design with three replications to evaluate five planting patterns [sole pearl millet, sole mungbean, and pearl millet + mungbean at 1:1, 2:1 and 2:2 row ratios] in main plots and four organic nutrient sources [control, 100% recommended dose of nitrogen (RDN) through farmyard manure (FYM), 75% RDN through FYM + two sprays of 10% vermiwash, and 50% RDN through FYM + vermiwash] in sub-plots. Sole crops recorded the highest component yields (pearl millet grain 1968 kg ha⁻¹; mungbean seed 983 kg ha⁻¹), and intercropping reduced pearl millet grain yield by 28.1–34.8% without altering harvest index. Nevertheless, all intercrops were land-use efficient: the 2:2 row ratio gave the highest land equivalent ratio (LER 1.302), pearl millet equivalent yield (PEY 3672 kg ha⁻¹, at par with sole mungbean), system relative crowding coefficient ($K = 3.48$) and monetary advantage index (852 kg PEY ha⁻¹). Partial LERs exceeding the sown proportions and near-zero aggressivity (± 0.11) in the 1:1 and 2:2 arrangements indicated balanced complementarity, whereas the 2:1 arrangement shifted the per-row competitive advantage to mungbean. Among organic sources, 75% RDN through FYM + vermiwash produced the highest pearl millet grain (1670 kg ha⁻¹) and mungbean seed (754 kg ha⁻¹) yields and PEY (3635 kg ha⁻¹), 34.6–37.8% above the control and statistically equivalent to 100% RDN through FYM, indicating that two vermiwash sprays could substitute for one-quarter of the FYM-N requirement. Pearl millet + mungbean in a 2:2 row ratio supplied with 75% RDN through FYM + vermiwash is identified as a promising low-input system for semi-arid conditions, subject to multi-season validation.

Keywords: Aggressivity, Farmyard manure, Land equivalent ratio, Organic nutrient management, Pearl millet equivalent yield, Relative crowding coefficient, Row ratio, Vermiwash

1. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is the principal cereal of the arid and semi-arid regions of India, and Rajasthan accounts for the largest share of its national area. Globally the crop occupies about 30 million hectares, mainly in Africa and Asia (Raheem *et al.*, 2021) [1], and is grown for both human food and livestock fodder in dryland areas (Victor *et al.*, 2023) [2]. In India it is cultivated on 7.36 million ha with a production of 11.20 million tonnes and a productivity of 1523 kg ha⁻¹ (Anonymous, 2024–25) [3]. Its tolerance of drought, low soil fertility and high temperature allows cultivation in environments where maize or wheat fail (Basavaraj *et al.*, 2010) [4], and its nutritional value has led to its recognition as a climate-resilient “nutri-cereal” (Satyavathi *et al.*, 2021) [5].

The scarcity of additional cropland and declining soil fertility threaten the long-term sustainability of agricultural production in these regions. Productivity must therefore be raised through more efficient use of existing land and nutrient resources. One such approach is intercropping, in which an additional population of a second crop is accommodated by modifying the planting geometry of the main crop (Renu *et al.*, 2018) [6]. Because sole cereal cultivation is increasingly less remunerative, integrating pulses into cereal-based systems can help meet the diverse nutritional needs of a growing population. Legumes improve soil fertility through biological nitrogen fixation and are therefore ideal companions for cereals (Victor *et al.*, 2023) [2]. Intercropping advantages arise from complementary resource use and facilitation between species that differ in stature, rooting pattern and duration (Zhang *et al.*, 2003; Brooker *et al.*, 2015) [8, 7], and the spatial arrangement of the component crops strongly influences productivity, economics, soil fertility and energetics in a region- and crop-specific manner (Kumar *et al.*, 2006) [9].

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Mungbean [*Vigna radiata* (L.) R. Wilczek] is an important short-duration (70–90 days) warm-season legume that is drought tolerant, requires few inputs and fixes atmospheric nitrogen (Pataczek *et al.*, 2018; Hou *et al.*, 2019) [11, 10]. In India, it occupies about 5.54 million ha with a production of 3.67 million t and a productivity of 663 kg ha⁻¹ (Anonymous, 2024–25) [3]. Its short stature and early maturity make it a suitable companion for the taller, longer-duration pearl millet, and pearl millet–mungbean intercrops have given yield advantages in arid Rajasthan (Ram *et al.*, 2014) [12] and in the Sahel (Diatla *et al.*, 2020) [13]. However, the optimum row ratio remains location-specific, and relatively few studies have quantified the competitive interactions underlying such advantages.

Intensive use of chemical fertilizers and pesticides to maximize productivity has contributed to soil degradation, erosion, and groundwater and atmospheric pollution, and to a decline in the nutritional quality of food. Organic sources such as farmyard manure (FYM) supply nutrients to both plants and soil micro-organisms and improve the physical, chemical and biological properties of soil (Diacono *et al.*, 2010) [14]. Vermiwash, the liquid collected from vermicomposting units, contains soluble nutrients, growth-promoting substances and beneficial microbes and can be applied as a foliar spray (Das *et al.*, 2014; Khan *et al.*, 2014; Oyege *et al.*, 2023) [15, 16, 17]. Whether foliar vermiwash can partly substitute for bulky FYM, which is often in short supply, has rarely been tested in cereal–legume intercrops.

Moreover, legume-integrated intercrops are known to reduce the requirement for external nitrogen (Jensen *et al.*, 2020) [18], which makes them a natural platform for organic nutrient management. Against this background, the present investigation was conducted during *kharif* 2023 with the objectives of (i) identifying the most productive and land-use-efficient row ratio of pearl millet + mungbean intercropping, (ii) characterizing the competitive interactions between the component crops using a set of complementary indices, and (iii) determining whether vermiwash sprays can reduce the FYM-N requirement without yield penalty.

2. Materials and Methods

2.1. Experimental site, climate and soil

The experiment was conducted on plot No. 9 of the Agronomy Farm, S.K.N. College of Agriculture, Jobner, Rajasthan, India (26°05' N, 75°28' E; 427 m above mean sea level), about 45 km west of Jaipur. The site lies in agro-climatic zone III-A (semi-arid eastern plain zone) of Rajasthan. Summer temperatures may reach 48 °C and winter temperatures may fall to –1.5 °C. Total rainfall during the crop season was 403.8 mm, received from the south-west monsoon between July and September. The soil was loamy sand, low in organic carbon and available nitrogen, medium in available phosphorus and potassium, and alkaline in reaction (Table 1).

Values are for a composite sample drawn before sowing.

Table 1. Physico-chemical properties of the experimental soil (0–15 cm) at the start of the experiment.

Property	Value	Method	Reference
Textural class	Loamy sand	USDA textural triangle	Soil Survey Staff (1975)
Organic carbon (%)	0.19	Rapid titration	Walkley and Black (1934)
Available nitrogen (kg ha ⁻¹)	132.3	Alkaline KMnO ₄	Subbiah and Asija (1956)
Available phosphorus (kg ha ⁻¹)	18.8	Olsen's NaHCO ₃ extraction	Olsen <i>et al.</i> (1954)
Available potassium (kg ha ⁻¹)	189.45	Flame photometry	Jackson (1973)
pH (1:2 soil:water)	8.21	Glass-electrode pH meter	Jackson (1973)
EC (1:2, 25 °C; dS m ⁻¹)	1.22	Conductivity meter	Jackson (1973)

2.2. Experimental design and treatments

The experiment was laid out in a split-plot design with three replications. Five planting patterns were assigned to main plots: I₁, sole pearl millet; I₂, sole mungbean; I₃, pearl millet + mungbean (1:1); I₄, pearl millet + mungbean (2:1); and I₅, pearl millet + mungbean (2:2). Four organic nutrient sources were assigned to sub-plots: O₁, control (no nutrient application); O₂, 100% recommended dose of nitrogen (RDN) through FYM; O₃, 75% RDN through FYM + two foliar sprays of vermiwash at 10%; and O₄, 50% RDN through FYM + two foliar sprays of vermiwash at 10%. The seeds of mungbean variety RMG 492 @ 15 kg/ha and pearl millet variety RHB 233 @ 5 kg/ha were used for sowing in the experiment. The sowing was done on 15 July 2023. The seeds were sown in rows 30 cm apart for sole crops. In intercropping situation second and third row of pearl millet were replaced by one row of mungbean in the pearl millet + mungbean (1:1) and pearl millet + mungbean (2:1) intercropping system, respectively.

While in pearl millet + mungbean (2:2) intercropping system third and fourth rows of pearl millet are replaced by two rows of mungbean (figure 1). Gross plot size was 4.0 m X 3.6 m, and the net plot size was 3.0 m X 2.4 m. Nitrogen (N), Phosphorus (P₂O₅), and Potash (K₂O) content in FYM were 0.51, 0.25, and 0.52%, respectively. Vermiwash diluted with water were applied at 30 DAS, and at 45 DAS using a battery-operated knapsack sprayer.

2.3. Grain, stover and biological yield and harvest index

At maturity the border rows were harvested first, after which the net plot of each crop was harvested separately, bundled, sun-dried and threshed. Grain/seed was cleaned and weighed, and stover/straw weight was recorded after threshing; both were converted to kg ha⁻¹. Biological yield was the sum of grain/seed and stover/straw yields, and harvest index (HI) was calculated using below formula (Singh *et al.*, 1971) [19].

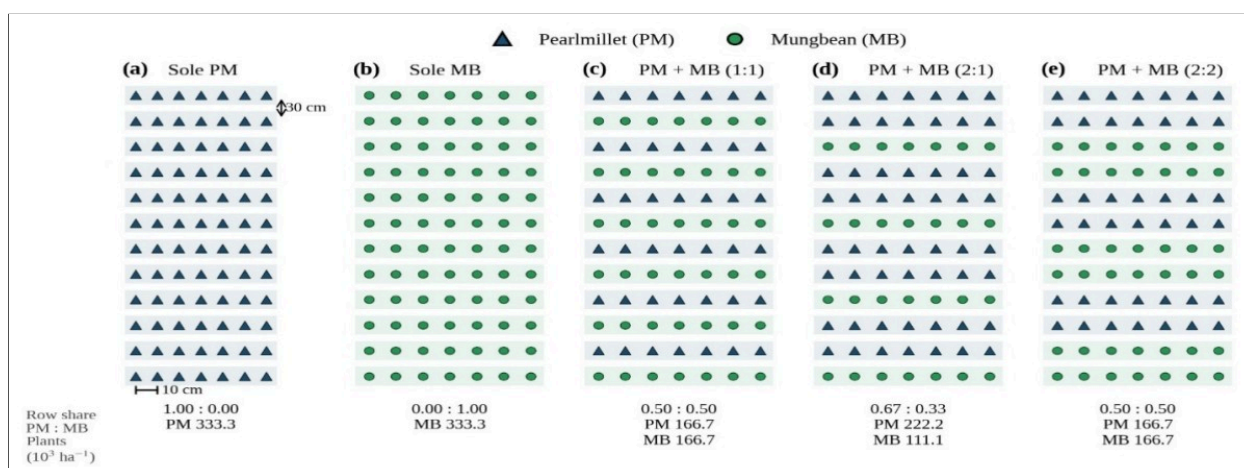


Figure 1. Planting geometry of sole and intercropping pattern of pearl millet and mungbean crops.

$$HI (\%) = (\text{economic yield/biological yield}) \times 100$$

2.4. System productivity and competition indices

Pearlmillet equivalent yield (PEY)

$$PEY = \frac{Y_{PM} + (Y_{MB} \times P_{MB})}{P_{PM}}$$

where Y_{PM} and Y_{MB} are the grain and seed yields (kg ha^{-1}) and P_{PM} and P_{MB} the prices (₹ kg^{-1}) of pearl millet and mungbean, respectively.

Land equivalent ratio (LER) (Mead *et al.*, 1980) [20]

$$LER = L_{PM} + L_{MB} = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}}$$

where Y_{ab} and Y_{ba} are the intercrop yields of pearl millet and mungbean and Y_{aa} and Y_{bb} their sole-crop yields; L_{PM} and L_{MB} are the partial LERs.

To characterize the competitive relationship between the components, the following indices were calculated,

Aggressivity (McGilchrist, 1965) [21],

$$APM = \frac{Y_{ab}}{(Y_{aa} \times Z_{ab})} - \frac{Y_{ba}}{(Y_{bb} \times Z_{ba})}$$

$$AMB = -APM$$

where Z_{ab} and Z_{ba} are the sown proportions of pearl millet and mungbean in the intercrop (0.50 and 0.50 for 1:1 and 2:2; 0.667 and 0.333 for 2:1). $A = 0$ denotes equal competitive ability and a positive value denotes dominance.

Competitive ratio (Willey *et al.*, 1980) [22],

$$CRPM = (LPM/Z_{ab}) / (LMB/Z_{ba})$$

$$CRMB = 1/CRPM$$

Relative crowding coefficient (de Wit, 1960) [23],

$$k_{PM} = Y_{ab} \times Z_{ba} / [(Y_{aa} - Y_{ab}) \times Z_{ab}]$$

$$k_{MB} = (Y_{ba} \times Z_{ab}) / [(Y_{bb} - Y_{ba}) \times Z_{ba}]$$

$$K = k_{PM} \times k_{MB}$$

$K > 1$ indicates a yield advantage.

Actual yield loss (Banik *et al.*, 2006) [24],

$$AYLPM = [(Y_{ab}/Z_{ab}) / (Y_{aa}/Z_{aa})] - 1$$

$$AYLMB = [(Y_{ba}/Z_{ba}) / (Y_{bb}/Z_{bb})] - 1$$

$$AYL = AYLPM + AYLMB$$

positive values indicate a per-plant gain relative to sole cropping.

Monetary advantage index (Willey, 1979; Ghosh, 2004) [26, 25]

$$MAI = PEY \times (LER - 1) / LER$$

system productivity index (Amanullah *et al.*, 2020) [27]

$$SPI = (Y_{aa}/Y_{bb}) \times Y_{ba} + Y_{ab}$$

MAI and SPI were expressed in pearl millet-equivalent units (kg ha^{-1}).

2.5. Statistical analysis

Data were subjected to analysis of variance appropriate to a split-plot design (Gomez *et al.*, 1984) [28]. The standard error of the mean ($\text{SEM} \pm$) and critical difference (CD) at $P = 0.05$ were computed for each factor, and treatment means were separated by the CD test; homogeneous groups are indicated by superscript letters. For yield variables specific to one crop, the main-plot factor comprised four levels (the respective sole crop and the three intercrops), giving 6 and 24 error degrees of freedom for main and sub-plots; PEY and LER were analysed over all five planting patterns (8 and 30 error df). The main-effect F-ratios in Table 3 were obtained as $F = \Sigma(\bar{y}_i - \bar{y})^2 / [(a - 1) \times \text{SEM}^2]$, which, for a balanced design equals the ratio of treatment to error mean squares; the coefficients of variation implied by these error terms reproduced the reported CVs to within 0.2 percentage points. Competition and economic indices were derived from treatment-mean yields averaged over organic sources. To visualize multi-variate treatment performance, variables were standardized to z-scores within each factor and displayed as heatmaps. Computations and figures were produced in Python (NumPy, SciPy, Matplotlib). Planting pattern $\times$ organic source interaction was non-significant for all the parameters.

3. Results

3.1. Grain and seed yield

Sole pearl millet produced the highest grain yield (1968 kg ha^{-1}), significantly more than all intercrops, which did not differ from one another ($1283\text{--}1415 \text{ kg ha}^{-1}$; Table 2, Fig. 2a). Grain yield under sole

cropping exceeded that under the 1:1, 2:2 and 2:1 row ratios by 53.4, 47.7 and 39.0%, respectively; equivalently, intercropping reduced pearl millet grain yield by 28.1–34.8%, with the smallest reduction in the 2:1 ratio, which allocated the largest share of rows to pearl millet. Sole mungbean likewise produced the highest seed yield (983 kg ha⁻¹). Among intercrops, the 2:2 ratio (613 kg ha⁻¹) gave significantly higher mungbean seed yield than the 2:1 ratio (505 kg ha⁻¹) and was at par with the 1:1 ratio (582 kg ha⁻¹). Sole mungbean out-yielded the 2:1, 1:1 and 2:2 intercrops by 94.6, 68.9 and 60.3%, respectively (Fig. 2b).

Organic nutrient sources significantly affected the yield of both crops (Table 2, Fig. 3). Application of 75% RDN through FYM + vermiwash produced the highest pearl millet grain yield (1670 kg ha⁻¹), which was significantly greater than the control (1241 kg ha⁻¹) and 50% RDN through FYM + vermiwash (1476 kg ha⁻¹), by 34.6 and 13.1%, and at par with 100% RDN through FYM (1612 kg ha⁻¹). Mungbean responded similarly: 75% RDN through FYM + vermiwash (754 kg ha⁻¹) exceeded the control (547 kg ha⁻¹) and 50% RDN through FYM + vermiwash (656 kg ha⁻¹) by 37.8 and 14.9%, and was at par with 100% RDN through FYM (726 kg ha⁻¹).

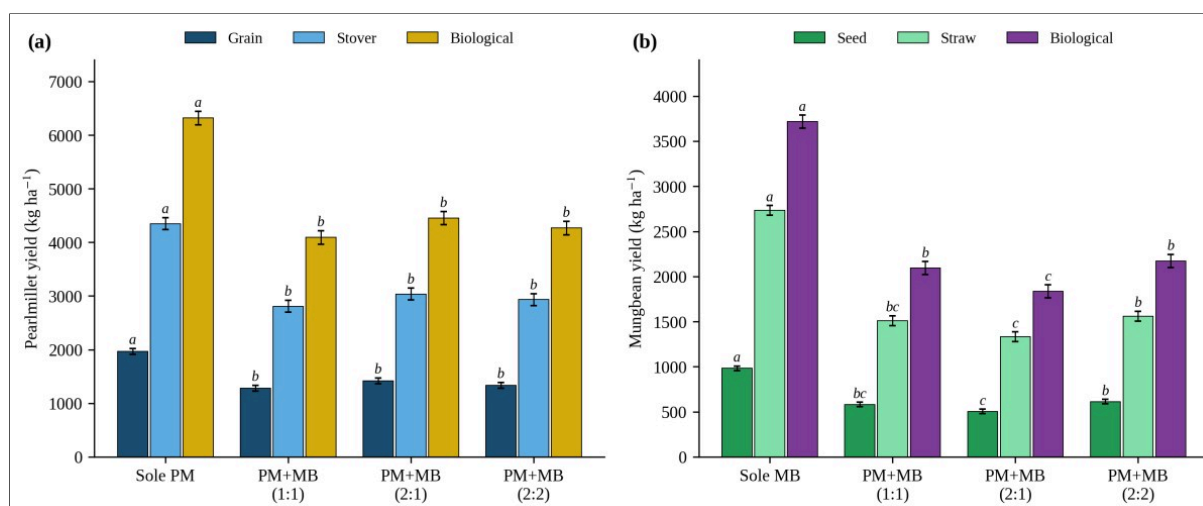


Figure 2. Effect of planting pattern on (a) grain, stover and biological yield of pearl millet and (b) seed, straw and biological yield of mungbean. Bars are treatment means averaged over organic nutrient sources; error bars represent the pooled SEM of the main-plot analysis. Within each yield component, bars sharing a common letter do not differ significantly (CD, $P = 0.05$). PM, pearl millet; MB, mungbean.

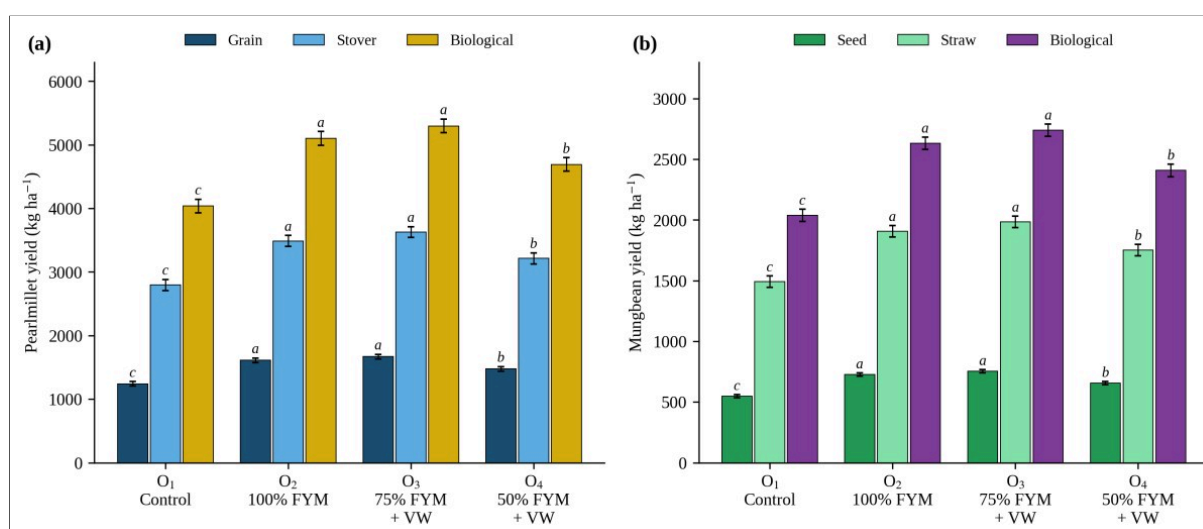


Figure 3. Effect of organic nutrient source on (a) grain, stover and biological yield of pearl millet and (b) seed, straw and biological yield of mungbean. O₁, control; O₂, 100% RDN through FYM; O₃, 75% RDN through FYM + two sprays of 10% vermiwash (VW); O₄, 50% RDN through FYM + VW. Bars are means averaged over planting patterns; error bars show the pooled SEM of the sub-plot analysis; common letters within a component indicate no significant difference (CD, $P = 0.05$).

Within a column and factor, means followed by a common superscript letter do not differ significantly according to the critical difference (CD) at $P = 0.05$; letters are not shown for non-significant effects (NS). RDN, recommended dose of nitrogen; FYM, farmyard manure; VW, two foliar sprays of vermiwash at 10%. Sub-plot LER is not applicable (–) because LER was computed per planting pattern.

3.2. Stover, straw and biological yield

Sole pearl millet produced significantly higher straw yield (4348 kg ha⁻¹) than the intercrops, which did not differ among themselves; the advantage of sole cropping over the 1:1, 2:2 and 2:1 ratios was 54.8, 48.2 and 43.2%, respectively. Sole mungbean gave the highest stover yield (2733 kg ha⁻¹), exceeding the 2:1, 1:1 and 2:2 ratios by 105.3,

81.0 and 75.2%. Among intercrops, the 2:2 ratio produced significantly more mungbean stover than the 2:1 ratio and was at par with the 1:1 ratio. Biological yield followed the same trend: sole pearl millet (6317 kg ha⁻¹) and sole mungbean (3717 kg ha⁻¹) were significantly superior to all intercrops; intercropped pearl millet did not differ among row ratios, whereas mungbean biological yield under the 2:2 ratio (2173 kg ha⁻¹) was at par with 1:1 (2093 kg ha⁻¹) and significantly higher than 2:1 (1836 kg ha⁻¹).

Application of 75% RDN through FYM + vermiwash increased pearl millet stover yield by 29.8 and 12.9% and mungbean straw yield (1985 kg ha⁻¹) by 33.0 and 13.4% over the control (1492 kg ha⁻¹) and 50% RDN through FYM + vermiwash (1751 kg ha⁻¹), respectively, and was at par with 100% RDN through FYM (1906 kg ha⁻¹).

The same treatment gave the highest biological yield of pearl millet (5298 kg ha⁻¹) and mungbean (2739 kg ha⁻¹), which exceeded the control (4037 and 2039 kg ha⁻¹) by 31.2 and 34.3% and 50% RDN through FYM + vermiwash (4691 and 2408 kg ha⁻¹) by 12.9 and 13.7%, respectively, while remaining at par with 100% RDN through FYM (5101 and 2633 kg ha⁻¹).

3.3. Harvest index and biomass partitioning

Harvest index was not significantly affected by planting pattern or organic source in either crop (Table 2, Table 3). Pearl millet HI remained within a narrow range of 30.8–31.8% and mungbean HI within 26.5–

28.2% across all treatments (Fig. 4). Thus, the yield responses to both factors were driven by proportional changes in total biomass rather than by altered partitioning between grain and straw. The slightly higher HI of intercropped mungbean (27.5–28.2%) compared with sole mungbean (26.5%), although not significant, is consistent with reduced vegetative crowding in the wider inter-row spaces of the intercrops.

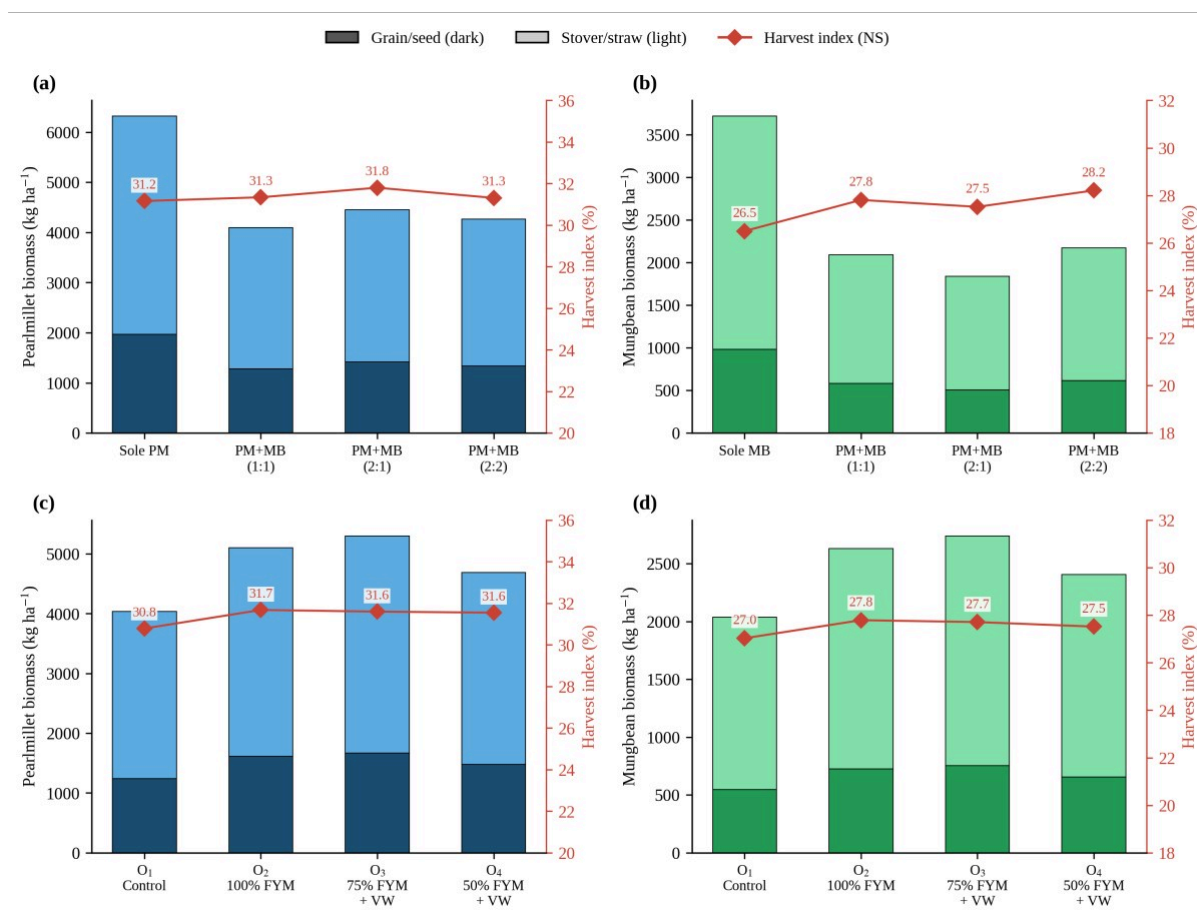


Figure 4. Biomass partitioning into grain/seed (dark segment) and stover/straw (light segment) and harvest index (diamonds, right axis) of pearl millet (a, c) and mungbean (b, d) as influenced by planting pattern (a, b) and organic nutrient source (c, d). Harvest index was not significantly affected by either factor (NS), indicating that treatment effects on grain yield operated through total biomass rather than altered partitioning.

3.4. Pearl millet equivalent yield

Sole mungbean recorded the highest PEY (3747 kg ha⁻¹), significantly higher than sole pearl millet and the 1:1 and 2:1 ratios, but at par with the 2:2 ratio (3672 kg ha⁻¹; Fig. 5b). Among intercrops, the 2:2 ratio was significantly superior to the 2:1 ratio (3340 kg ha⁻¹) and

at par with the 1:1 ratio (3503 kg ha⁻¹). All intercrops produced 70–87% more PEY than sole pearl millet (1968 kg ha⁻¹). Among organic sources, 75% RDN through FYM + vermiwash produced the highest PEY (3635 kg ha⁻¹), 36.6 and 14.2% higher than the control and 50% RDN through FYM + vermiwash, and at par with 100% RDN through FYM (3505 kg ha⁻¹; Fig. 5c).

Table 2. Effect of planting pattern and organic nutrient source on grain/seed, stover/straw and biological yield, harvest index, pearl millet equivalent yield (PEY) and land equivalent ratio (LER) of pearl millet (PM) and mungbean (MB).

Treatment	Grain/seed yield (kg ha ⁻¹)		Stover/straw yield (kg ha ⁻¹)		Biological yield (kg ha ⁻¹)		Harvest index (%)		PEY (kg ha ⁻¹)	LER
	PM	MB	PM	MB	PM	MB	PM	MB		
<i>Planting pattern (main plot)</i>										
I ₁ – Sole pearl millet	1,968 ^a	–	4,348 ^a	–	6,317 ^a	–	31.16	–	1,968 ^d	1.000 ^c
I ₂ – Sole mungbean	–	983 ^a	–	2,733 ^a	–	3,717 ^a	–	26.50	3,747 ^a	1.000 ^c
I ₃ – PM + MB (1:1)	1,283 ^b	582 ^{bc}	2,809 ^b	1,510 ^{bc}	4,092 ^b	2,093 ^b	31.34	27.81	3,503 ^{bc}	1.259 ^{ab}
I ₄ – PM + MB (2:1)	1,415 ^b	505 ^c	3,036 ^b	1,331 ^c	4,452 ^b	1,836 ^c	31.80	27.52	3,340 ^c	1.230 ^b
I ₅ – PM + MB (2:2)	1,333 ^b	613 ^b	2,933 ^b	1,560 ^b	4,267 ^b	2,173 ^b	31.31	28.21	3,672 ^{ab}	1.302 ^a
SEm±	53	25	109	55	125	72	0.96	0.75	74	0.020
CD (<i>P</i> = 0.05)	182	85	378	192	433	248	NS	NS	242	0.064
CV (%)	12.1	12.7	11.5	10.8	9.1	10.1	10.5	9.4	7.9	5.9
<i>Organic nutrient source (sub-plot)</i>										
O ₁ – Control	1,241 ^c	547 ^c	2,796 ^c	1,492 ^c	4,037 ^c	2,039 ^c	30.79	27.03	2,661 ^c	–
O ₂ – 100% RDN through FYM	1,612 ^a	726 ^a	3,489 ^a	1,906 ^a	5,101 ^a	2,633 ^a	31.68	27.79	3,505 ^a	–
O ₃ – 75% RDN through FYM + VW	1,670 ^a	754 ^a	3,628 ^a	1,985 ^a	5,298 ^a	2,739 ^a	31.60	27.71	3,635 ^a	–
O ₄ – 50% RDN through FYM + VW	1,476 ^b	656 ^b	3,214 ^b	1,751 ^b	4,691 ^b	2,408 ^b	31.55	27.52	3,183 ^b	–
SEm±	35	14	86	47	107	51	0.58	0.54	72	–
CD (<i>P</i> = 0.05)	102	40	252	136	313	148	NS	NS	209	–
CV (%)	8.1	7.1	9.1	9.1	7.8	7.1	6.4	6.8	8.7	–

3.5. Land equivalent ratio

All intercroops recorded LER > 1, indicating a 23–30% land-use advantage over sole cropping (Table 4, Fig. 5a). The 2:2 ratio gave the highest LER (1.302), which was significantly greater than that of the 2:1 ratio (1.230) and sole crops (1.000) and at par with the 1:1 ratio (1.259). Partitioning of LER showed that pearl millet contributed 0.65–0.72 and mungbean 0.51–0.62 of the total. In every arrangement

both partial LERs exceeded the corresponding sown proportions (0.50 or 0.667 for pearl millet; 0.50 or 0.333 for mungbean), meaning that each species produced more per unit of allocated area in the intercrop than in the sole stand. The largest mungbean partial LER (0.624) and hence the highest total LER was obtained in the 2:2 arrangement, whereas the 2:1 arrangement favoured pearl millet (0.719) at the expense of mungbean (0.514).

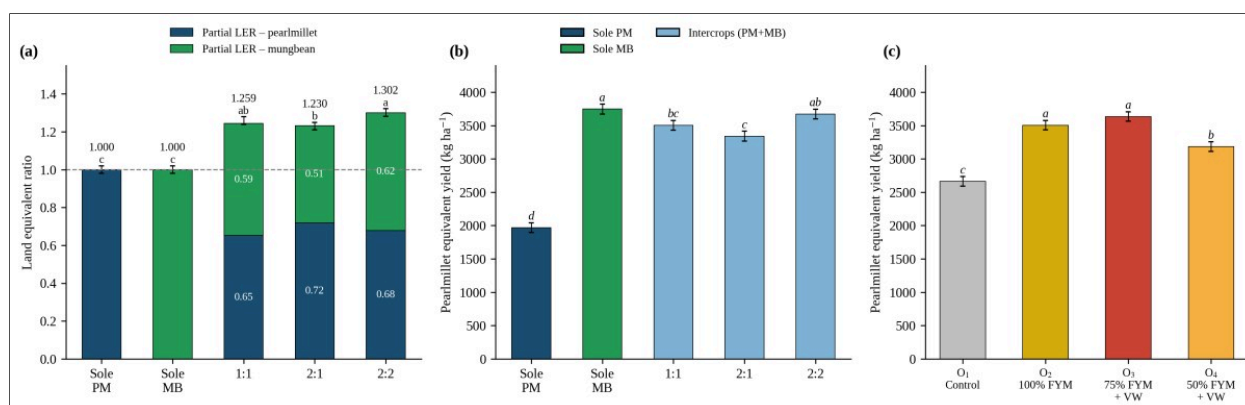


Figure 5. System productivity of pearl millet + mungbean intercropping. (a) Land equivalent ratio (LER) partitioned into partial LERs of pearl millet and mungbean (values inside segments, from treatment means); the value and letter above each bar are the reported plot-level LER; the dashed line marks LER = 1. (b) Pearl millet equivalent yield (PEY) across planting patterns. (c) PEY across organic nutrient sources. Error bars are pooled SEM; common letters indicate no significant difference (CD, *P* = 0.05).

3.6. Competition indices

Aggressivity values were close to zero in the 1:1 ($A_{PM} = +0.12$) and 2:2 ($+0.11$) arrangements, indicating that pearl millet was only marginally more competitive than mungbean and that the two species exploited resources almost equally (Table 3, Fig. 6a). In the 2:1 arrangement, however, A_{PM} was strongly negative (-0.46) and CR_{MB} rose to 1.43, showing that on a per-row basis mungbean outperformed pearl millet when a single mungbean row was flanked by paired

pearl millet rows (Fig. 6b). The relative crowding coefficients of both species exceeded unity in all arrangements, and the system K ranged from 2.70 (2:1) to 3.48 (2:2), confirming a yield advantage (Fig. 6c). Partial AYL values were positive for both crops in all row ratios, and system AYL ranged from 0.49 (1:1) to 0.62 (2:1) (Fig. 6d). In the 2:1 ratio the AYL gain was concentrated in mungbean (0.54 vs. 0.08 for pearl millet), whereas in the 1:1 and 2:2 ratios it was shared more evenly between the components.

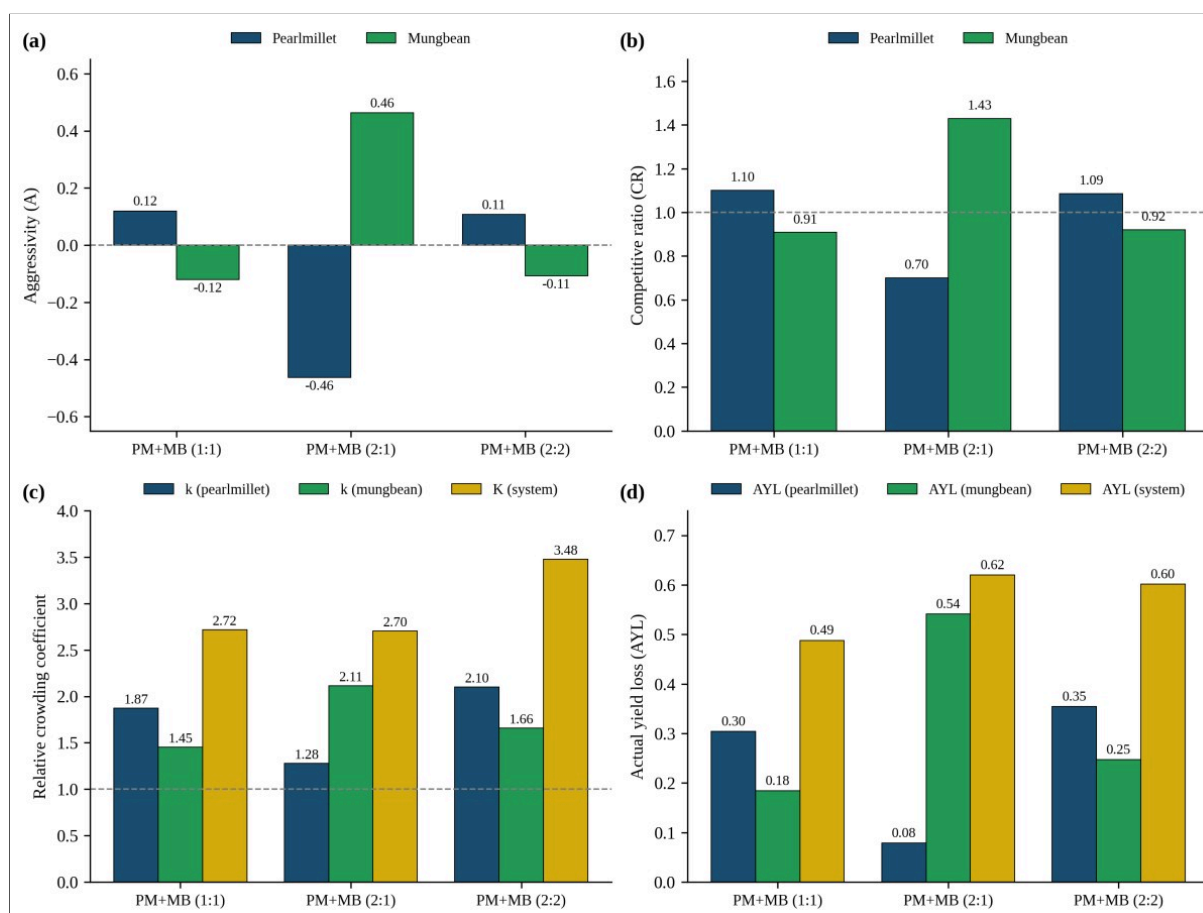


Figure 6. Competition indices of pearl millet and mungbean at 1:1, 2:1 and 2:2 row ratios: (a) aggressivity, (b) competitive ratio, (c) relative crowding coefficients of each species (k) and of the system (K), and (d) partial and system actual yield loss (AYL). Dashed lines indicate the neutral value of each index ($A = 0$, $CR = 1$, $K = 1$). Indices were calculated from treatment-mean yields assuming a replacement series.

Table 3. Partial and total land equivalent ratios, competition indices and economic advantage indices of pearl millet + mungbean intercropping at different row ratios.

Index	1:1	2:1	2:2	Interpretation
Partial LER – pearl millet (L_{PM})	0.652	0.719	0.677	$> Z_{PM}$: gain
Partial LER – mungbean (L_{MB})	0.592	0.514	0.624	$> Z_{MB}$: gain
LER from treatment means	1.244	1.233	1.301	> 1 : land-use advantage
LER (plot-level, reported)	1.259	1.230	1.302	> 1 : land-use advantage
Aggressivity of pearl millet (A_{PM})	0.120	-0.463	0.107	0: equally competitive; + PM dominant
Competitive ratio – pearl millet (CR_{PM})	1.101	0.700	1.086	> 1 : PM more competitive
Competitive ratio – mungbean (CR_{MB})	0.908	1.429	0.921	> 1 : MB more competitive
Relative crowding coefficient – pearl millet (k_{PM})	1.873	1.279	2.099	
Relative crowding coefficient – mungbean (k_{MB})	1.451	2.113	1.657	
System relative crowding coefficient (K)	2.718	2.703	3.478	> 1 : yield advantage
Actual yield loss – pearl millet (AYL_{PM})	0.304	0.079	0.355	+ : gain per plant
Actual yield loss – mungbean (AYL_{MB})	0.184	0.541	0.247	+ : gain per plant
Actual yield loss – system (AYL)	0.488	0.620	0.602	+ : intercrop advantage
Monetary advantage index (kg PEY ha ⁻¹)	721	625	852	+ : economic advantage
System productivity index (kg ha ⁻¹)	2448	2426	2560	higher = more productive

Indices were computed from treatment-mean yields (averaged over organic sources) assuming a replacement series with sown proportions $Z_{PM}/Z_{MB} = 0.50/0.50$ (1:1 and 2:2) and $0.667/0.333$ (2:1). $A_{MB} = -A_{PM}$. MAI and SPI are expressed in pearl millet-equivalent units using the mungbean:pearl millet price ratio (3.81) implied by the PEY values. Small differences between LER from means and the reported plot-level LER arise because the mean of ratios differs from the ratio of means.

3.7. Economic advantage of intercropping

The monetary advantage index was positive in all intercrops, ranging from 625 (2:1) to 852 kg PEY ha⁻¹ (2:2), and the system productivity index followed the same order (2:2, 2560 > 1:1, 2448 > 2:1, 2426 kg ha⁻¹; Table 4). When LER and PEY were considered jointly (Fig. 7), the 2:2 arrangement occupied the upper-right position, combining the highest land-use efficiency with a PEY statistically equivalent to that of sole mungbean, whereas the 2:1 arrangement was the least efficient intercrop on both axes.

3.8. Nitrogen substitution by vermiwash

The yield response to organic sources ranked $O_3 > O_2 > O_4 > O_1$ for every yield variable (Table 4, Fig. 8a). Relative to the control, O_3 increased yields by 29.8–37.8%, O_2 by 24.8–32.7% and O_4 by 14.9–19.9%. Mungbean seed yield was the most responsive variable (37.8% under O_3) and pearl millet stover the least (29.8%). When expressed relative to 100% RDN through FYM (Fig. 8b), O_3 attained 103.6–104.1% of O_2 for all variables (differences not significant), whereas O_4 attained only 90.4–92.1% (differences significant). Thus, two foliar sprays of 10% vermiwash fully compensated for a 25% reduction in FYM-N, but not for a 50% reduction.

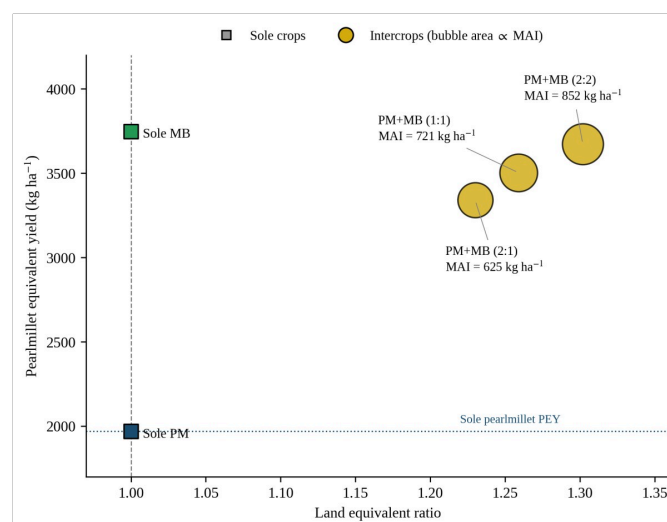


Figure 7. Relationship between land equivalent ratio and pearl millet equivalent yield for sole crops (squares) and intercrops (circles). Bubble area is proportional to the monetary advantage index (MAI, kg PEY ha⁻¹). The vertical dashed line marks LER = 1 and the dotted horizontal line the PEY of sole pearl millet. The 2:2 row ratio occupies the upper-right position, combining the highest land-use efficiency with the highest economic advantage among intercrops.

Table 4. Relative response of yield variables to organic nutrient sources and nitrogen-substitution test against 100% RDN through FYM.

Variable	O_1 control (kg ha ⁻¹)	O_2 vs O_1 (%)	O_3 vs O_1 (%)	O_4 vs O_1 (%)	O_3 as % of O_2	O_4 as % of O_2
Pearlmillet grain yield	1,241	29.9	34.6	18.9	103.6 (NS)	91.6 (S)
Pearlmillet stover yield	2,796	24.8	29.8	14.9	104.0 (NS)	92.1 (S)
Pearlmillet biological yield	4,037	26.4	31.2	16.2	103.9 (NS)	92.0 (S)
Mungbean seed yield	547	32.7	37.8	19.9	103.9 (NS)	90.4 (S)
Mungbean straw yield	1,492	27.7	33.0	17.4	104.1 (NS)	91.9 (S)
Mungbean biological yield	2,039	29.1	34.3	18.1	104.0 (NS)	91.5 (S)
Pearlmillet equivalent yield	2,661	31.7	36.6	19.6	103.7 (NS)	90.8 (S)

O_2 , 100% RDN through FYM; O_3 , 75% RDN through FYM + vermiwash (10%, two sprays); O_4 , 50% RDN through FYM + vermiwash. S / NS, difference from O_2 significant / not significant at $P = 0.05$ (CD test). A non-significant O_3 – O_2 contrast indicates that vermiwash compensated for a 25% reduction in FYM-N.

3.9. Overview of treatment effects

Planting pattern and organic nutrient source both had highly significant ($P < 0.001$) effects on grain/seed, stover/straw and biological yield of the two crops and on PEY, while planting pattern also significantly affected LER (Table 5). Neither factor influenced the harvest

index of either crop ($P \geq 0.47$). The F-ratios for mungbean straw (135.7) and biological yield (140.6) under planting pattern were the largest in the dataset, reflecting the strong dependence of mungbean biomass on its share of the land area, whereas organic sources exerted the greatest relative effect on mungbean seed yield ($F = 43.4$) and PEY ($F = 36.3$). The standardized profiles in Figure 9 summarize these patterns: sole crops scored highest for component yields but lowest for LER, the 2:2 row ratio combined above-average LER, PEY and mungbean HI, and O_3 occupied the most favourable position across all yield variables among organic sources.

Table 5. Analysis of variance (F-test) for the main effects of planting pattern and organic nutrient source on yield and system-productivity variables.

Variable	F (PP)	df	P	F (OS)	df	P
Pearlmillet grain yield	35.75***	3, 6	< 0.001	29.69***	3, 24	< 0.001
Mungbean seed yield	72.63***	3, 6	< 0.001	43.39***	3, 24	< 0.001
Pearlmillet stover yield	43.27***	3, 6	< 0.001	18.18***	3, 24	< 0.001
Mungbean straw yield	135.65***	3, 6	< 0.001	21.37***	3, 24	< 0.001
Pearlmillet biological yield	68.40***	3, 6	< 0.001	27.12***	3, 24	< 0.001
Mungbean biological yield	140.58***	3, 6	< 0.001	36.86***	3, 24	< 0.001
Pearlmillet harvest index	0.08ns	3, 6	0.967	0.51ns	3, 24	0.680
Mungbean harvest index	0.95ns	3, 6	0.475	0.40ns	3, 24	0.755
Pearlmillet equivalent yield	97.73***	4, 8	< 0.001	36.30***	3, 30	< 0.001
Land equivalent ratio	53.78***	4, 8	< 0.001	—	—	—

(continued on next page)

PP, planting pattern (main plot); OS, organic nutrient source (sub-plot); df, numerator and error degrees of freedom. **, $P^* < 0.001$; ns, not significant. F-ratios were derived from the treatment means and pooled SEM of the split-plot analysis (see Section 2.6); reconstructed coefficients of variation reproduced the reported CVs to within 0.2

percentage points. For pearl millet- and mungbean-specific variables the main-plot factor has four levels (the respective sole crop plus three intercrops); for PEY and LER all five planting patterns are included.

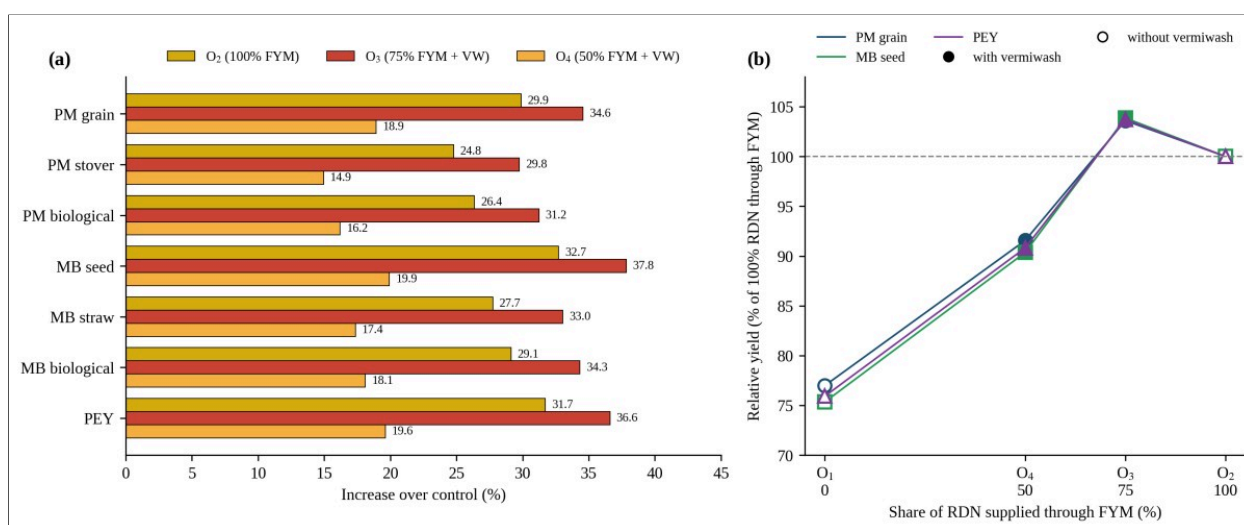


Figure 8. Response of pearl millet and mungbean to organic nutrient sources. (a) Percentage increase over the unfertilized control (O₁) for seven yield variables. (b) Relative yield (% of 100% RDN through FYM, O₂) plotted against the share of RDN supplied through FYM; filled symbols denote treatments receiving two foliar sprays of 10% vermiwash, open symbols treatments without vermiwash. The dashed line marks parity with O₂.

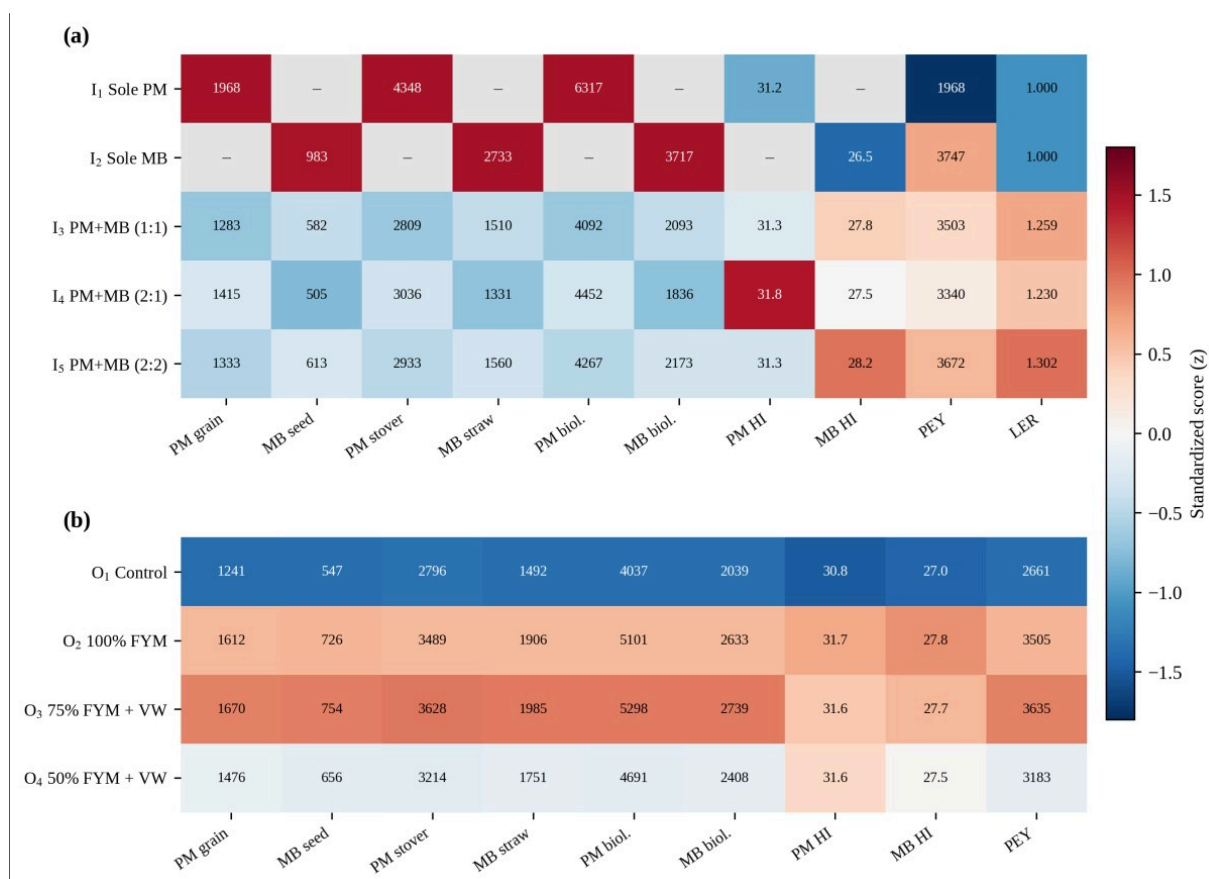


Figure 9. Heatmaps of standardized (z-score) performance across all measured variables for (a) planting patterns and (b) organic nutrient sources. Colours represent the standardized deviation of each treatment from the factor mean for that variable (red, above mean; blue, below mean); cell values are the original treatment means. Grey cells (—) denote variables not applicable to the planting pattern. Standardization was performed within each factor; harvest-index columns should be read in light of their non-significance (Table 5).

4. Discussion

4.1. Component yields and yield attributes under

intercropping

Intercropping with mungbean significantly increased the number of tillers plant⁻¹ of pearl millet, particularly in the 2:2 and 1:1 row ratios, whereas ear-head length was unaffected. This response can be attrib

uted to the more favourable micro-environment created by the short-statured legume: reduced intraspecific competition among pearl millet plants in the wider inter-row spaces and the transfer of part of the biologically fixed nitrogen from the legume rhizosphere to the cereal, which promoted growth and yield-attribute formation (Zhang *et al.*, 2003; Duchene *et al.*, 2017) [8, 29]. Similar increases in tillering of intercropped pearl millet were reported by Kuri *et al.* (2012) [30] and Yadav *et al.* (2015) [31], and Amanullah *et al.* (2020) [27] observed more grains head⁻¹ in pearl millet grown with mungbean than in sole stands.

Despite these per-plant gains, intercropping reduced pearl millet grain, stover and biological yields per hectare, because the reduced plant population per unit area in the replacement arrangements could not be fully offset by the improvement in individual plant performance. Among row ratios, the 2:1 arrangement recorded the highest pearl millet yields, followed by the 2:2 and 1:1 arrangements, in proportion to the share of land allocated to the cereal. Comparable reductions in component yields under intercropping have been documented by Yadav *et al.* (2015) [31], Victor *et al.* (2023) [2] and Amanullah *et al.* (2020) [27]. Pearl millet did not affect the yield attributes of mungbean (pods plant⁻¹ and seeds pod⁻¹), but sole mungbean produced significantly higher seed and straw yields than the intercrops, again primarily because of its larger plant population. These findings agree with Tripathi *et al.* (2005) [32], who reported substantial reductions in chickpea yield when intercropped with mustard, and with Yadav *et al.* (2014) [33] for moth bean–pearl millet intercropping. The stability of harvest index across planting patterns (Fig. 3) indicates that neither crop altered its assimilate partitioning under intercropping, so yield differences reflected differences in biomass production per unit area.

4.2. Land-use advantage and complementarity

Although each component yielded less than its sole crop, the combined system used land 23–30% more efficiently than sole cropping. That the partial LERs of both species exceeded their sown proportions in every arrangement indicates genuine complementarity rather than a transfer of yield from one species to the other (Mead *et al.*, 1980) [20]. Pearl millet, a tall C₄ cereal of longer duration, and mungbean, a short C₃ legume that matures earlier, differ in canopy height, rooting depth, nitrogen source and phenology. Such temporal and spatial niche differentiation is the principal driver of LER gains in annual intercrops (Yu *et al.*, 2015; Li *et al.*, 2020) [35, 34], and the partial relief of the cereal from nitrogen competition by the legume adds a facilitative component (Brooker *et al.*, 2015; Bedoussac *et al.*, 2015) [7, 36]. The LER values obtained here (1.23–1.30) are comparable to those reported for pearl millet–mungbean systems in arid Rajasthan (Ram *et al.*, 2014) [12] and in Senegal, where LER consistently exceeded unity across mungbean densities (Diatte *et al.*, 2020) [13].

The superiority of the 2:2 arrangement arose mainly from the higher mungbean partial LER (0.62), suggesting that paired mungbean rows experienced less shading from the adjacent cereal than single mungbean rows did in the 1:1 arrangement, while paired pearl millet rows retained a partial LER (0.68) close to that of the 2:1 arrangement. Paired-row arrangements also facilitate intercultural operations and harvesting of the two crops separately, which favours their adoption by farmers.

4.3. Competitive interactions

The competition indices provide a mechanistic explanation for the differences among row ratios. Near-zero aggressivity and competitive ratios close to unity in the 1:1 and 2:2 arrangements indicate a balanced interaction in which neither species strongly suppressed the other, which is the condition generally associated with maximum intercrop advantage (Dhima *et al.*, 2007) [37]. Pearl millet was slightly dominant in these arrangements, in agreement with Amanullah *et al.* (2020) [27], who found the cereal to be the more aggressive component in pearl millet–mungbean intercrops, and with Ram *et al.* (2014) [12], who reported that mungbean offered little competition to

pearl millet. In contrast, the 2:1 arrangement produced a strongly negative A_{PM} and a mungbean CR of 1.43. In this arrangement, each mungbean row had pearl millet on both sides and no mungbean neighbour, so its intraspecific competition was minimal and its per-row yield was high relative to the small area allocated to it, whereas paired pearl millet rows competed with each other for water and nutrients on the low-fertility loamy sand. The index therefore reflects a per-row advantage rather than an absolute suppression of pearl millet, and it did not translate into a higher system LER. System K values between 2.70 and 3.48 and positive AYL for both components (Banik *et al.*, 2006) [24] confirm that all three arrangements were advantageous, with the 2:2 ratio showing the strongest mutual benefit. Because these indices were calculated from treatment means under an assumed replacement series, their absolute values should be interpreted with caution; nevertheless, their ranking was consistent with the independently analysed LER and PEY.

4.4. Economic implications

Owing to the higher market price of mungbean (a price ratio of about 3.8 relative to pearl millet), sole mungbean recorded the highest PEY. However, the 2:2 intercrop was statistically at par with sole mungbean in PEY while additionally producing about 1.3 t ha⁻¹ of pearl millet grain and 2.9 t ha⁻¹ of stover, a critical fodder resource for livestock-based farming in western Rajasthan (Satyavathi *et al.*, 2021) [5]. Intercropping also spreads the risk of crop failure under erratic monsoon rainfall, a benefit not captured by single-season PEY. The positive MAI of all intercrops, highest for the 2:2 ratio, confirms that the biological advantage was converted into an economic one (Willey, 1979; Ghosh, 2004) [26, 25]. A full economic analysis including cost of cultivation, net returns and benefit:cost ratio is needed to confirm these conclusions.

4.5. Organic nutrient management and substitution of FYM by vermiwash

Both crops responded strongly to organic nutrient sources on this soil, which was low in organic carbon (0.19%) and available nitrogen (132.3 kg ha⁻¹). FYM improves soil structure, water-holding capacity and microbial activity and releases nutrients gradually over the season (Diacono *et al.*, 2010) [14], which accounts for the large yield increase over the unfertilized control. The key finding is that 75% RDN through FYM supplemented with two sprays of 10% vermiwash was statistically equivalent to, and numerically 3.6–4.1% higher than, 100% RDN through FYM for all yield variables. Vermiwash supplies readily absorbable nutrients, plant-growth-regulating substances such as auxins and cytokinins, enzymes and beneficial micro-organisms (Das *et al.*, 2014; Oyege *et al.*, 2023) [15, 17], and foliar vermiwash has been shown to increase plant nitrogen supply and alter shoot nutrient stoichiometry (Khan *et al.*, 2014) [16]. Applied at critical growth stages, these inputs appear to have bridged the nutrient gap created by the reduction in FYM, while the basal FYM maintained soil nutrient supply. When FYM was halved (O₄), however, yields fell significantly below O₂ (90–92%), indicating that foliar vermiwash cannot substitute for the soil-applied organic N beyond a threshold on such N-deficient soils.

The consistently higher yield attributes under O₃ (tillers, ear-head length, pods plant⁻¹ and seeds pod⁻¹) explain its yield advantage, and the unchanged harvest index indicates that the organic sources increased total source–sink capacity rather than partitioning. The slightly greater relative response of mungbean (37.8%) than of pearl millet (34.6%) may reflect the stimulation of nodulation and early vigour of the legume by the growth-promoting substances and microbes in FYM and vermiwash. Because legume-integrated intercrops reduce the requirement for external nitrogen (Jensen *et al.*, 2020) [18], combining an efficient row arrangement with partial substitution of FYM by vermiwash offers a practical route to lowering organic-input requirements in semi-arid systems where FYM is scarce.

5. Conclusions

Intercropping pearl millet with mungbean reduced the yield of each component relative to its sole crop but increased land-use efficiency by 23–30%. The 2:2 row ratio was the most efficient arrangement, recording the highest LER (1.302), system relative crowding coefficient (3.48) and monetary advantage index, and a PEY at par with sole mungbean, while providing pearl millet grain and fodder. Balanced competitive interactions in the 1:1 and 2:2 arrangements underpinned this advantage, whereas the 2:1 arrangement favoured mungbean on a per-row basis without improving system productivity. Application of 75% RDN through FYM with two sprays of 10% vermiwash gave the highest yields of both crops and PEY, equivalent to 100% RDN through FYM, thereby saving one-quarter of the FYM requirement. Pearl millet + mungbean in a 2:2 row ratio with 75% RDN through FYM + vermiwash is therefore recommended as a promising low-input practice for the semi-arid eastern plain zone of Rajasthan, pending multi-season validation.

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Conflict of interest

The authors declare no conflict of interest.

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