



Economic viability and energy use in legume-zero-till maize (*Zea mays*) cropping system under nitrogen fertility levels in irrigated conditions

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ABSTRACT

Recent advancement in pulse production supplementing cereal as a year-round productivity with suboptimal fertilizer using the residual waste as means of cost subjugation for sustainable resource cycle was analyzed in zero-till conditions on cost effectiveness and energy balance sheets. The present study was carried out during rainy (*kharif*) and winter (*rabi*) season of 2021–22 and 2022–23 at Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad, Telangana to evaluate the economic aspects influenced by the preceding legumes on *rabi* maize. The experiment was laid out in a split plot design (SPD) in 3 replications. Treatments were framed with 6 main-plots, viz. C₁N₁, Groundnut (*Arachis hypogaea*)_{100%RDN}-maize (*Zea mays* L.); C₁N₂, Groundnut_{75%RDN}-maize; C₂N₁, Soybean (*Glycine max* L.)_{100%RDN}-maize; C₂N₂, Soybean_{75%RDN}-maize; C₃N₁, Greengram (*Vigna radiata* L.)_{100%RDN}-maize; C₃N₂, Greengram_{75%RDN}-maize and 3 sub-plots, viz. 100% RDN, 125% RDN, 150% RDN. The output data signified higher individual (1,28,463 ₹/ha) and overall net returns (2,09,902 ₹/ha), B-C ratio (3.41), system profitability (1043 ₹/ha/day), productivity (70.93 kg/ha/day) and energetics viz. energy ratio, net energy (2,87,660 MJ/ha), energy productivity (0.580 Kg/MJ × 10³) with prior green gram with 100% RDN on *rabi* maize followed by soybean and groundnut, respectively. Subsequently with nitrogen levels, 150% RDN showed its supremacy in output economical and energy balance sheets over lesser doses (125% and 100% RDN). However, interaction among the treatments i.e. (legume residues × nitrogen levels in *rabi*) was statistically found to be non-significant in 2 years of study.

Keywords: B-C ratio, Energy productivity, Profitability, Residues, System net returns

Maize (*Zea mays* L.) stands out as an exceptionally versatile crop, thriving across diverse agro-climatic conditions. Recognized globally as the premier cereal, maize boasts the highest genetic yield potential among its counterparts (Singh *et al.* 2021). Cultivated across approximately 190 million hectares in 165 countries, its cultivation spans a wide range of soil types, climates, biodiversity, and agricultural management approaches. This extensive presence contributes significantly, accounting for 39% of global grain production (Rani *et al.* 2021).

In India, maize is cultivated during both the *kharif* and *rabi* seasons. While *kharif* maize accounts for approximately

83% of the total maize area, *rabi* maize constitutes about 17%. Notably, *rabi* maize often achieves higher productivity, averaging 4,436 kg/ha, compared to 2,706 kg/ha for *kharif* maize. Approximately, 10% of the country's total food grain production comes from maize, making it the third most important cereal crop after rice and wheat.

Based on FAO data statistics for 2023–24, India was the fifth-largest producer, with a production estimate about 35.67 million tonnes, representing 2.59% of global production in the year.

Maize, beyond being a fundamental staple for humans and high-quality feed for animals, serves as a crucial raw material in numerous industrial sectors. Its applications span a vast array of products including starch, oil, protein, alcoholic beverages, sweeteners, pharmaceuticals, cosmetics, films, textiles, gums, packaging, and paper (Naab *et al.* 2017). In India, maize is predominantly cultivated as a *kharif* crop, with 85% of cultivation occurring during this season. Globally, maize stands out as a top cereal, excelling not only in productivity but also in its versatility as a source of human sustenance, animal nutrition, and a wide range of industrial goods (Samant *et al.* 2015).

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Meeting the evolving needs of future generations through the enhanced utilization of maize poses unique challenges for researchers. Currently, approximately 55% of maize is consumed as food, with additional uses including feed, forage, and processing. In India, 55% of grain production is allocated to food purposes, while 14% is used for livestock feed, 18% for poultry feed, 12% for starch, and 1% for seed (Salisu *et al.* 2022). Looking ahead to the end of the century, demand is projected to shift, with an estimated 46% for food, 14% for livestock feed, 19% for poultry feed, 19% for starch industry, and 15% for seed (Rajashekarappa *et al.* 2013).

Further, the outcomes of profit are a major functionary for any system to workout in present conditions. With the positive yield potential and market value that showed a time and space driven momentum throughout the year. Apart from the *kharif* crops, added with varied level of nitrogen could be a better for evaluation on economic aspects. So, the current research was streamlined to evaluate the economic aspects influenced by the preceding legumes on *rabi* maize.

MATERIALS AND METHODS

The present study was carried out during rainy (*kharif*) and winter (*rabi*) season of 2021–22 and 2022–23 at Professor Jayashankar Telangana Agricultural University, Rajendranagar (17°19'N and 78°23'E with elevation of 542.3 m msl), Hyderabad, Telangana. The location has been categorized as semi-arid tropics based on Troll's Classification. In both years, the weather conditions were congenial for the overall system with range of minimum (12.6° to 21.2°C) and maximum temperature (26.3° to 33.2°C). Further the rainfall was ideal about 878.54 mm. The study was framed with 6 main-plots, viz. (C₁N₁, Groundnut_{100%} RDN⁻ maize; C₁N₂, Groundnut_{75%} RDN⁻ maize; C₂N₁, Soybean_{100%} RDN⁻ maize; C₂N₂, Soybean_{75%} RDN⁻ maize; C₃N₁, Greengram_{100%} RDN⁻maize; C₃N₂, Greengram_{75%} RDN⁻ maize) and 3 subplots, viz. F₁, 100% RDN; F₂, 125% RDN; F₃, 150% RDN in *rabi* with 3 replications in split-plot design.

Kharif legumes were sown on June 25th with a spacing of 30 cm × 10 cm in area of 1500 m². Zero-till maize was planted on September 25th for green gram and October 23rd for soybean and groundnut with a spacing of 60 cm × 20 cm. Additionally, P₂O₅, K₂O @80 kg/ha as a basal and 20, 60, 20, 240 kg N/ha for groundnut, soybean green gram and maize, respectively.

Control measured were taken based on recommendations. The individual and overall system economical aspects i.e. cost of cultivation, gross returns, net returns and B:C ratio was calculated as per existing MSP. The statistical analysis of data pertaining to legume-maize system with nitrogen levels in split-plot design was worked in SPSS software to compare the data and to look for treatment variation was calculated using ANOVA, and at a 5% probability level, significant variation across treatments was determined using the critical difference (CD) (Steel and Torrie 1980).

Cost of cultivation (₹/ha): The cost of cultivation was

calculated on the basis of prevailing charges for different inputs i.e. labour, equipment, seed, chemicals, etc. The cost of treatment included the hourly rate for the operating tractor and, the cost of fertilizer rates for every plot as the case may be.

$$\text{Cost of cultivations with treatment (₹/ha)} = \text{Cost of treatment (₹/ha)} + \text{Cost of cultivation (₹/ha)}.$$

Gross monetary returns (₹/ha): Gross return is the prevailing market price of grain and haulm yield of individual crops i.e. (groundnut, soybean, green gram and maize) at the time of harvest.

Net monetary returns (₹/ha): Net return from each treatment was calculated separately by subtracting the cost of cultivation from the gross return and expressed as per ha.

$$\text{Net monetary return} = \text{Gross monetary return} - \text{Total cost of cultivation}.$$

Benefit: cost ratio: Benefit-cost ratio was calculated by using the following formula:

$$\text{B:C ratio} = \frac{\text{Gross returns (₹/ha)}}{\text{Cost of cultivation (₹/ha)}}$$

System productivity (kg/ha/day): System productivity in terms of maize equivalent yield (MEY) was calculated by multiplying the economic yield of groundnut, soybean and greengram with price per quintal of individual crops and divided by price per quintal of maize in the local market by making use of the following formula as stated by Munda *et al.* (2007).

$$\text{Maize equivalent yield (q/ha)} = \frac{\text{Yield of maize crop} + \text{Yield of groundnut/soybean/greengram (q)} \times \text{price per q}}{\text{Price of maize per q (as per local market)}}$$

$$\text{System productivity} = \text{Maize yield} + \text{Maize equivalent yield (q/ha)}$$

Land use efficiency (%): The land use efficiency was worked out by dividing total duration of crops in individual sequence by 365 and multiplied by 100 (Kermah *et al.* 2017).

System profitability (₹/ha/day): Production efficiency values were obtained by dividing total net returns of a sequence by total duration of crop sequence (Saad *et al.* 2015).

Energetics: The energetics approach quantifies input materials and outputs in terms of energy. Direct energy includes labour, machinery, fuel, and electricity, while indirect energy covers inputs like seeds, fertilizers, and chemicals. Energy input from different legume residues in maize was assessed using this framework. Energy was assessed for producing implements, seeds, manure, fertilizers, and chemicals. A complete inventory of crop inputs and seed yield was recorded at different growth stages.

Energy input was determined by multiplying each input with its energy coefficient and summing the values. Output energy was calculated by multiplying pod yield with its respective energy coefficient. Indirect energy use of

agricultural machineries was calculated by using equation (Salama *et al.* 2021).

$$E_{im} = (MTR \times M) / (L \times C_e)$$

Where E_{im} , Machinery input energy (MJ/ha); MTR, Energy used to manufacture, transport and repair; M, Mass of machinery; L, Life of machinery; C_e , Effective field capacity of farm machinery (h/ha)

Energy efficiencies of the legume-maize sequences were estimated as

Energy ratio:

$$\text{Energy ratio} = \frac{\text{Output energy (MJ/ha)}}{\text{Input energy (MJ/ha)}}$$

Net energy:

Net energy returns = Output energy (MJ/ha) - Input energy (MJ/ha)

Energy productivity (kg/MJ):

$$\text{Energy productivity} = \frac{\text{Total yield (kg/ha)}}{\text{Energy input (MJ/ha)}}$$

RESULTS AND DISCUSSION

Evaluation of individual rabi maize: Over two years

of study, preceding greengram with 100% recommended nitrogen dose (RDN) in the legume-zero-till maize system resulted in significantly higher gross and net returns, as well as a superior benefit-cost (B:C) ratio, followed by soybean and greengram with 100% and 75% RDN, respectively. Among nitrogen levels, the application of 150% RDN in zero-till maize yielded significantly higher economic returns compared to 125% and 100% RDN. However, the interaction (Legume residues $\times$ Nitrogen gradient levels) was statistically non-significant during the 2021–22 and 2022–23 cropping seasons (Table 1). The notable increase in the monetary values in *rabi* maize with greengram residues could be due to higher mobilization of resources effectively along the crop phenophase that paved for the higher growth and yield attributes that counterpart in better yield potential. The alike findings were in Raskar *et al.* (2013) and Singh *et al.* (2017).

Evaluation of cropping system: The 2021–22 and 2022–23 research studies found that applying 100% RDN to green gram in *kharif*, followed by *rabi* maize, yielded greater overall system gross, net returns, and B:C ratios than with applying 75% RDN to green gram, and using 75 and 100% RDN to soybean and groundnut. In relation to nitrogen levels in zero-till *rabi* maize when applied with

Table 1 Monetary returns of zero-till *rabi* maize as influenced by *kharif* legumes and nitrogen fertility levels during 2021–22 and 2022–23

Treatments	Gross returns (₹/ha)			Net returns (₹/ha)			B:C		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
<i>Kharif</i> legumes $\times$ nitrogen levels (C $\times$ N)									
C ₁ N ₁ , Groundnut _{100%} RDN	151450	156001	153726	92633	101185	96909	2.69	2.78	2.74
C ₁ N ₂ , Groundnut _{75%} RDN	138919	141987	140453	81103	84170	82637	2.40	2.45	2.42
C ₂ N ₁ , Soybean _{100%} RDN	161304	167923	164614	103487	113106	108297	2.79	2.95	2.87
C ₂ N ₂ , Soybean _{75%} RDN	156645	162807	159726	98106	107991	103049	2.74	2.86	2.81
C ₃ N ₁ , Greengram _{100%} RDN	183159	189399	186279	125342	131583	128463	3.17	3.27	3.22
C ₃ N ₂ , Greengram _{75%} RDN	168952	173190	171071	117802	120373	119088	2.92	3.04	2.98
SEM $\pm$	1580	1562	-	1681	1285	-	0.03	0.02	-
CD ($p=0.05$)	4578	4921	-	5297	4050	-	0.09	0.07	-
<i>Rabi</i> maize with varied nitrogen fertility levels (F)									
F ₁ , 100% RDN	147719	150836	149277.5	90608	93725	92167	2.59	2.64	2.61
F ₂ , 125% RDN	160823	167999	164411	101339	110184	105762	2.78	2.91	2.84
F ₃ , 150% RDN	174673	179318	176995.5	115039	120795	117917	2.98	3.06	3.02
SEM $\pm$	3034	1032	-	2292	978	-	0.06	0.02	-
CD ($p=0.05$)	8854	3012	-	6688	2853	-	0.18	0.05	-
Interaction									
Sub treatments at same level of main treatments F $\times$ (C $\times$ N)									
SEM $\pm$	6975	2123	-	5124	2013	-	0.11	0.03	-
CD ($p=0.05$)	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at same/different level of sub treatments (C $\times$ N) $\times$ F									
SEM $\pm$	7431	2527	-	5613	2394	-	0.15	0.04	-
CD ($p=0.05$)	NS	NS	-	NS	NS	-	NS	NS	-

Table 2 Overall system monetary returns of zero-till *rabi* maize as influenced by *kharif* legumes and nitrogen fertility levels during 2021–22 and 2022–23

Treatments	System-Gross returns (₹/ha)			System-Net returns (₹/ha)			System- B:C		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
<i>Kharif</i> Legumes × nitrogen levels (C×N)									
C ₁ N ₁ , Groundnut _{100%} RDN	292503	300772	296637	147210	162939	155074	2.36	2.44	2.4
C ₁ N ₂ , Groundnut _{75%} RDN	264068	273123	268595	133718	143529	138623	2.30	2.39	2.34
C ₂ N ₁ , Soybean _{100%} RDN	250512	266241	258376	169191	187911	178551	2.62	2.69	2.65
C ₂ N ₂ , Soybean _{75%} RDN	236873	246684	241778	152365	167421	159893	2.43	2.58	2.50
C ₃ N ₁ , Greengram _{100%} RDN	283038	311043	297040	195900	223905	209902	3.25	3.57	3.41
C ₃ N ₂ , Greengram _{75%} RDN	255269	277357	266313	180741	191278	186009	2.96	3.22	3.09
SEM±	3387	6605	-	1321	999	-	0.02	0.02	-
CD (<i>p</i> =0.05)	10672	20810	-	4163	3149	-	0.05	0.07	-
<i>Rabi</i> maize with varied nitrogen fertility levels (F)									
F ₁ , 100% RDN	250358	263988	257173	150541	164171	157356	2.54	2.68	2.61
F ₂ , 125% RDN	263462	281152	272307	162939	180629	171784	2.65	2.84	2.74
F ₃ , 150% RDN	277312	292470	284891	176083	191241	183662	2.77	2.93	2.85
SEM±	2170	7337	-	1283	822	-	0.02	0.01	-
CD (<i>p</i> =0.05)	6332	21411	-	3744	2399	-	0.05	0.04	-
Interaction									
Sub treatments at same level of Main treatments F × (C × N)									
SEM±	5024	17231	-	4023	2457	-	0.03	0.02	-
CD (<i>p</i> =0.05)	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at same/different level of sub treatments (C × N) × F									
SEM±	5314	17971	-	4306	2656	-	0.04	0.03	-
CD (<i>p</i> =0.05)	NS	NS	-	NS	NS	-	NS	NS	-

Table 3 System productivity, Profitability and Land use efficiency as influenced by *kharif* legumes and nitrogen fertility levels on zero-till *rabi* maize during 2021–22 and 2022–23

Treatments	System Profitability (₹/ha/day)			System Productivity (kg/ha/day)			LUE (%)		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
<i>Kharif</i> Legumes × nitrogen levels (C × N)									
C ₁ N ₁ , Groundnut _{100%} RDN	632	656	644	61.69	58.18	59.94	66.03	67.40	66.72
C ₁ N ₂ , Groundnut _{75%} RDN	608	610	609	55.69	51.99	53.84	66.03	67.40	66.72
C ₂ N ₁ , Soybean _{100%} RDN	750	802	776	59.12	56.89	58.01	60.27	60.82	60.55
C ₂ N ₂ , Soybean _{75%} RDN	669	734	701	54.52	53.62	54.07	60.27	60.27	60.27
C ₃ N ₁ , Greengram _{100%} RDN	994	1092	1043	72.95	68.90	70.93	53.97	56.16	55.07
C ₃ N ₂ , Greengram _{75%} RDN	859	933	896	65.69	61.69	63.69	53.97	56.16	55.07
SEM±	17	12	-	0.22	0.23	-	4.04	3.94	-
CD (<i>p</i> =0.05)	54	39	-	0.66	0.69	-	NS	NS	-
<i>Rabi</i> maize with varied nitrogen fertility levels (F)									
F ₁ , 100% RDN	694	740	717	58.26	55.24	56.75	60.09	61.37	60.73
F ₂ , 125% RDN	752	814	783	62.06	58.98	60.52	60.09	61.37	60.73
F ₃ , 150% RDN	811	878	844	64.51	61.41	62.96	60.09	61.37	60.73
SEM±	9	15	-	0.36	0.40	-	2.83	2.76	-
CD (<i>p</i> =0.05)	26	45	-	1.04	1.18	-	NS	NS	-
Interaction									
Sub treatments at same level of Main treatments F × (C × N)									
SEM±	21	35	-	0.51	0.75	-	6.02	5.95	-
CD (<i>p</i> =0.05)	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at same/different level of sub treatments (C × N) × F									
SEM±	22	38	-	0.88	0.99	-	6.94	6.76	-
CD (<i>p</i> =0.05)	NS	NS	-	NS	NS	-	NS	NS	-

150% RDN had exponential net returns, net rupee per input cost compared to lower doses (Table 2). Besides, the combination effect with legumes $\times$ nitrogen gradient levels on zero-till maize was proved to be non-significant. Monetary returns play a key role, for adopting the refined agro techniques. In the present study even though the gross returns were recorded higher with the *kharif* groundnut than green gram and soybean with *rabi* maize system, the system net returns and benefit cost ratio were higher with green gram as preceding legume during the *kharif* season followed by zero-till maize during *rabi*. This might be due to the high cost of cultivation of groundnut in *kharif* season compared to green gram and soybean. Similar findings were reported by Srinivasulu *et al.* (2020), Shukla *et al.* (2021) and Hulmani *et al.* (2022).

System profitability (₹/ha/day): Table 3 data indicate that greengram as a *kharif* legume at 100% recommended nitrogen dose (RDN) achieved significantly higher system profitability (₹ 994 and ₹1092/ha) compared to greengram at 75% RDN (₹859 and ₹933/ha), soybean at 100% RDN (₹ 750 and ₹802/ha), and groundnut at 75% RDN (₹608

and ₹610/ha) during 2021–22 and 2022–23, respectively. Furthermore, *rabi* maize at 150% RDN exhibited superior system productivity (811 and 878 kg/ha) compared to 125% RDN (752 and 814 kg/ha), while the lowest productivity was recorded at 100% RDN (694 and 740 kg/ha), underscoring the role of optimized nitrogen management in enhancing cropping system performance. The interaction effects among the treatments were statistically non-significant across both years, aligning with the findings of Samant (2015) and Singh *et al.* (2016).

System productivity (kg/ha/day): In 2021–22 and 2022–23 data, system productivity outperformed superior in green gram with 100% RDN (72.9 and 68.9) over green gram at 75% RDN (65.69 and 61.69), soybean and groundnut in zero-till *rabi* maize cropping sequence. Further, higher system profitability in maize with 150% RDN (64.51 and 61.41) compared to 125% RDN (62.06 and 58.98) and lowest in 100% RDN (58.26 and 55.24). Yet, the interaction (*kharif* legumes $\times$ nitrogen gradient levels) was found non-significant. The similar findings were reported by Jat *et al.* (2014) and Prabhamani and Babalad (2018). The

Table 4 Energy ratio, net energy, energy productivity as influenced by *kharif* legumes and nitrogen fertility levels on zero-till *rabi* maize during 2021–22 and 2022–23

Treatments	Net energy (MJ/ha)			Energy ratio (MJ/ha)			Pod energy productivity			Total energy productivity (Kg/MJ $\times 10^3$)		
	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean	2021–22	2022–23	Mean
<i>Kharif</i> legumes $\times$ Nitrogen levels (C $\times$ N)												
C ₁ N ₁ , Groundnut _{100%} RDN	258909	246704	252807	8.14	7.96	8.05	0.220	0.210	0.220	0.490	0.480	0.490
C ₁ N ₂ , Groundnut _{75%} RDN	223710	217305	220508	7.32	7.12	7.22	0.200	0.190	0.200	0.440	0.430	0.440
C ₂ N ₁ , Soybean _{100%} RDN	274270	268484	271377	8.78	8.59	8.69	0.240	0.230	0.240	0.530	0.520	0.530
C ₂ N ₂ , Soybean _{75%} RDN	258909	252425	255667	8.34	8.14	8.24	0.230	0.220	0.230	0.500	0.490	0.500
C ₃ N ₁ , Greengram _{100%} RDN	303256	272064	287660	9.82	9.40	9.61	0.270	0.270	0.270	0.590	0.570	0.580
C ₃ N ₂ , Greengram _{75%} RDN	278369	297465	287917	9.10	8.69	8.90	0.250	0.260	0.260	0.550	0.530	0.540
SEM $\pm$	1275	4770	-	0.06	0.08	-	0.001	0.001	-	0.001	0.002	-
CD ($p=0.05$)	3276	15029	-	0.20	0.24	-	0.013	0.014	-	0.013	0.014	-
<i>Rabi</i> maize with varied nitrogen fertility levels (F)												
F ₁ , 100% RDN	242875	236547	239711	8.51	8.11	8.31	0.210	0.200	0.210	0.500	0.490	0.500
F ₂ , 125% RDN	268229	262585	265407	8.58	8.31	8.45	0.220	0.210	0.220	0.510	0.500	0.510
F ₃ , 150% RDN	284452	278092	281272	8.65	8.43	8.54	0.230	0.230	0.230	0.530	0.520	0.530
SEM $\pm$	1427	3262	-	0.02	0.04	-	0.002	0.002	-	0.001	0.002	-
CD ($p=0.05$)	4165	9520	-	0.06	0.11	-	0.014	0.015	-	0.012	0.014	-
Interaction												
Sub treatments at same level of main treatments F $\times$ (C $\times$ N)												
SEM $\pm$	3402	7571	-	0.07	0.11	-	0.01	0.02	-	0.01	0.02	-
CD ($p=0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-
Main treatments at same/different level of sub treatments (C $\times$ N) $\times$ F												
SEM $\pm$	3496	7990	-	0.09	0.13	-	0.01	0.02	-	0.01	0.02	-
CD ($p=0.05$)	NS	NS	-	NS	NS	-	NS	NS	-	NS	NS	-

superior system productivity in green gram with 100% RDN suggested that optimal nitrogen availability enhances biomass accumulation and yield. Higher profitability in maize at 150% RDN indicated that increased nitrogen input improves grain production and economic returns, though with diminishing gains beyond 125% RDN.

Energetics: In terms of energetics, viz. net energy, energy ratio and energy productivity was significantly greater with prior green gram @100% RDN to succeeding maize in comparison to soybean and groundnut (100 and 75% RDN) (Table 4). Similarly, among varied nitrogen doses in winter maize, 150% RDN resulted higher energy outputs over 125% and 100% RDN. Nevertheless, the interaction with legume residues $\times$ nitrogen rates was found non-significant during 2021–22 and 2022–23. Thus, Modern crop energy production heavily relies on fossil energy inputs, including fuel, electricity, fertilizers, and pesticides, greatly affecting its efficiency. Productivity and profitability in agriculture now hinge on energy consumption, driven by agrochemicals and advanced cultivars. This analysis underscored the need for crucial enhancements towards a more eco-friendly and efficient production system. Similar results were obtained by Meena *et al.* (2015), Lal *et al.* (2019), Kang *et al.* (2019) and Laxmi *et al.* (2022).

The study firmly underscores the vitality of sustaining soil fertility by resource recycling for enhanced productivity in legume-maize cropping systems. The integration of *kharif* green gram followed by zero-till *rabi* maize with a full recommended dose of nitrogen demonstrated superior economic returns and energy efficiency. Green gram, being a short-duration crop with a high minimum support price (MSP), effectively aligns with the cropping sequence, optimizing resource utilization and maximizing system profitability. Over two years, this approach not only improved yield output but also enhanced energy balance, reinforcing its viability as a sustainable and efficient cropping system.

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