



Energy Dynamics and Efficiency of Aerobic Rice-blackgram Cropping System under Sustainable Nutrient Management Practices

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ABSTRACT

Background: This study focuses on assessing the energy use pattern and input-output balance in the aerobic rice-blackgram cropping system under various nutrient sources. The objective is to determine the energy efficiency by evaluating how different nutrient management practices influence energy utilization and crop productivity. Since optimizing energy use is crucial for achieving sustainable and cost-effective farming, the study aims to identify the most efficient and productive nutrient management approach suitable for the aerobic rice-blackgram system.

Methods: The field experiment was conducted in split plot design with three replication consisted of two main plot and six sub plot treatments during 2022 and 2023 at wetland farms, Tamil Nadu Agricultural University, Coimbatore. The main plots consisted of the cultivation of rice with and without green manure intercropping. The subplots consisted of different sources of nutrient management practices.

Result: The results revealed that incorporation of *daincha* (M_2) along with half dose of recommended nitrogen from inorganic fertilizer + quarter dose of recommended nitrogen from enriched farmyard manure + quarter dose of recommended nitrogen from vermicompost + AM fungi and foliar nutrients of 0.5% urea, 1% $FeSO_4$ and 0.5% $ZnSO_4$ (S_6) significantly improved the energy performance of the aerobic rice-blackgram system. This treatment increased the energy use efficiency by 10-43%, output energy by 11-60% and reduced energy input by 9.10-11.63% compared to application of inorganic fertilizer alone. These findings indicate that integration of different sources of nutrient enhances energy efficiency, reduces reliance on chemical fertilizers and contributes to sustainable system productivity.

Key words: Cropping sequence, Energy, Environmental sustainability, Resource utilization.

INTRODUCTION

Rice-based cropping systems are a cornerstone of food security in India, providing staple nutrition and livelihood to millions of farmers. Nonetheless, the heavy dependence on high-input cereal cultivation has led to extensive cereal monocropping, causing significant ecological imbalance, particularly in terms of soil degradation, loss of organic matter, nutrient depletion and poor soil structure. In contrast, legumes play a vital role in improving soil fertility through biological nitrogen fixation, enhancing soil microbial activity and contributing to sustainable nutrient cycling. Incorporating blackgram into rotation can help restore soil health, reduce dependency on chemical fertilizers and offer additional economic returns to farmers, making it a strategic choice for sustainable agriculture (Sangothari and Radhamani, 2026a). This approach contributes to the development of sustainable agriculture and a cleaner environment. To achieve a sustainable and cleaner agro-ecosystem, it is crucial to adopt agricultural management practices that require low energy inputs and enhanced energy use efficiency. In this regard, incorporating legumes into existing cropping systems can improve energy use efficiency by reducing the need for nitrogen fertilizer, thereby increasing overall system productivity (Sangothari and Radhamani, 2025b).

In contemporary farming, increasing the input energy level contribute to higher agricultural output. In the current

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scenario, effective energy management is crucial for achieving greater productivity, profitability and sustainability in agriculture. It contributes to the conservation of natural resources and mitigates environmental pollution, while also increasing profitability (Hazarika *et al.*, 2023). Farmers often adopt crop diversification and management practices, along with inputs, based on soil fertility, pest infestation and other agro-climatic conditions. However, a higher usage of fertilizers might only result in a minimal yield increase. Consequently, farmers may resort to using excessive agricultural inputs such as chemical fertilizers, pesticides, irrigation water and seed in an attempt to maximize

crop yield (Mobtaker *et al.*, 2010). Nevertheless, in many cases, increasing input energy in crop production does not necessarily maximize profit for the farmer. Instead, it often leads to higher production costs and reduced energy efficiency (Erdal *et al.*, 2007). In crop production, various forms of energy inputs are utilized. Crop production acts as both a sink and a source of bioenergy (Alam *et al.*, 2005). Achieving a net energy balance in crop production is possible when the energy input is lower and the output is higher (Mohammadi *et al.*, 2008).

Efficient energy assessment is crucial for the sustainable management of limited resources to enhance crop productivity in India, especially in the context of rapid natural resource depletion and climate change. Developing cropping system with resource efficient management practices to achieve higher energy efficiency with reduced energy inputs is key to ensuring economic sustainability and enhancing the livelihoods of farmers in Tamil Nadu.

MATERIALS AND METHODS

A field experiment to evaluate sustainable nutrient management in the aerobic rice-blackgram cropping system was carried out during 2022-2023 at the Wetland Farm of Tamil Nadu Agricultural University (TNAU), Coimbatore. The surface soil (0-15 cm) was clay loam in texture. Initial soil characterization showed low organic carbon (0.66 and 0.68 g ha⁻¹) and available nitrogen (210 and 222 kg ha⁻¹), medium level of available phosphorus (20.2 and 21.7 kg ha⁻¹) and high available potassium (690 and 699 kg ha⁻¹) for the two years. The field experiment followed a split-plot design with 12 treatments, replicated three times. Main plot treatments included M₁- Rice alone and M₂- Rice + *Dhaincha* intercropping and sub plot treatments were S₁- Control, S₂- Full dose of RDN (Recommended Dose of Nitrogen) from inorganic fertilizer, S₃ - Half dose of RDN from inorganic fertilizer + half dose of RDN from enriched farmyard manure (EFYM), S₄- Half dose of RDN from inorganic fertilizer + half dose of RDN from EFM + AM fungi + foliar nutrients (0.5% urea + 1% FeSO₄ + 0.5% ZnSO₄ at 25 and 45 DAS), S₅- Half dose of RDN from inorganic fertilizer + quarter dose of RDN from EFM + quarter dose of RDN from vermicompost (VC), top-dressed at 25 DAS and S₆- Half dose of RDN from inorganic fertilizer + quarter dose of RDN from EFM + quarter dose of RDN from VC + AM fungi + foliar nutrients (0.5% urea + 1% FeSO₄ + 0.5% ZnSO₄ at 25 and 45 DAS).

Rice seeds were sown directly into dry soil at a spacing of 20 × 10 cm. *Dhaincha* (*Sesbania aculeata*) was simultaneously sown in an additive series (1:1 ratio) as per the treatment schedule and the green manure crop was incorporated into the soil manually 25 days after sowing. The recommended fertilizer dose of 150:50:50 kg ha⁻¹ N:P:K was applied in four splits: 20% at 15 days after sowing, 30% each at the tillering and panicle initiation stages and the remaining 20% at flowering. Potassium was supplied in two equal portions, with half applied as a basal dose and the remainder at panicle initiation. After harvesting rice, blackgram was directly sown into the

standing rice stubble without additional land preparation. The succeeding blackgram crop received no fertilizers and depended entirely on the residual nutrients left from the preceding rice crop.

Energy analysis

Energy inputs and outputs

To assess the input and output energy, all crop inputs (including organic and inorganic fertilizers, seeds, plant protection chemicals, fuel, human labour and machinery power) as well as the output of both the main product and by product of aerobic rice and blackgram were converted from physical unit to energy unit using published conversion coefficients, as detailed in Table 1.

Energy indicators

The following equations were used to calculate the energy indicators.

Net energy (NE)

Net energy was calculated by subtracting energy input from energy output.

Energy use efficiency (EUE) =

$$\frac{\text{Total output energy (Mj ha}^{-1}\text{)}}{\text{Total input energy (Mj ha}^{-1}\text{)}}$$

$$\text{Specific energy (SE)} = \frac{\text{Total input energy (Mj ha}^{-1}\text{)}}{\text{Grain yield (Kg ha}^{-1}\text{)}}$$

$$\text{Energy intensiveness (EI)} = \frac{\text{Total input energy (Mj ha}^{-1}\text{)}}{\text{Cost of cultivation (Rs.ha}^{-1}\text{)}}$$

$$\text{Energy productivity (EPr)} = \frac{\text{Grain yield (Mj ha}^{-1}\text{)}}{\text{Energy input (Mj ha}^{-1}\text{)}}$$

Human energy profitability (HEP) =

$$\frac{\text{Economic output (Mj ha}^{-1}\text{)}}{\text{Labour energy (Mj ha}^{-1}\text{)}}$$

$$\text{Energy profitability (EPf)} = \frac{\text{Net energy gain (Mj ha}^{-1}\text{)}}{\text{Total input energy (Mj ha}^{-1}\text{)}}$$

Energy output efficiency (EOE) =

$$\frac{\text{Energy output (Mj ha}^{-1}\text{)}}{\text{Duration of the system (days)}}$$

Statistical analysis

All data were tested for normality using R software (v4.2.0) and found to be normally distributed. Treatment means were compared using the least significant difference (LSD) test at P≤0.05. Additionally, The psych package in R was utilized to reveal intricate associations within the dataset through analysis. A correlation plot, employing pearson correlation coefficient, provided valuable insights into the underlying structure of the data.

RESULTS AND DISCUSSION

Input energy consumption by crops

The energy consumed by the crops throughout their growth stages is illustrated in Fig 1 and 1a. The overall energy consumed by crops is calculated based on the energy expended on land preparation, seeds, plant protection, manures/fertilizers, labor and diesel. During both the years, the plot fertilized with the application of full dose of RDN through inorganic fertilizer recorded higher input energy (37% in 2022 and 41% in 2023, respectively) of aerobic rice - blackgram cropping sequence. Whereas, the lowest input energy (31% in 2022 and 35% in 2023, respectively) was recorded under combined application of inorganic, organic, AM fungi and foliar nutrients. The computation revealed variations in input energy levels, which could be attributed to differences in energy utilization under various nutrient management practices. The energy input for black gram production remained consistent across all treatments

since the crop was cultivated under residual N fertility with uniform application of P and K, along with consistent management practices. Furthermore, several researchers have previously reported lower total energy requirements for cropping systems that include legume crops (Malhi *et al.*, 2002). The reduced energy input associated with sustainable nutrient management strategies could be attributed to the lower energy of organic manures compared to chemical fertilizers. Higher energy input with the use of chemical fertilizers was earlier reported by Paramesh *et al.* (2019).

Response on output energy and net energy

The total energy output was calculated from both the main and the by-product of the cropping system. The results revealed that *dhaincha* intercropping (M_2) increased the total output energy (11.1%) and net energy (74583 MJ ha⁻¹) over sole rice (M_1). With regard to nutrient management strategies, plot treated half dose of RDN by inorganic fertilizer + quarter dose of RDN by EFYM + quarter dose of

Table 1: Details of energy values of input and output used.

Particulars	Unit	Energy value (MJ)	References
Inputs			
Implements			
Cultivator/ rotavator	MJ ha ⁻¹	64.80	Ugale (2014)
Animal (Bullock pair- medium)	MJ ha ⁻¹	10.10	
Human labour			
Man hour	MJ hr	1.96	Mittal (1985)
Women hour	MJ hr	1.57	
Fuel (Diesel)	MJ l ⁻¹	56.31	
Electricity	KW hr ⁻¹	11.93	
Seeds			
<i>Dhaincha</i>	MJ kg ⁻¹	14.70	Singh <i>et al.</i> (2022)
Rice	MJ kg ⁻¹		Mittal (1985)
Blackgram	MJ kg ⁻¹		
Biofertilizers			
AM fungi	MJ kg ⁻¹	10.0	Ugale (2014)
Organic inputs			
Farm yard manure	MJ kg ⁻¹	0.30	Mittal (1985)
Vermicompost	MJ kg ⁻¹		
Chemical fertilizer			
Nitrogen	MJ kg ⁻¹	60.0	Gathala <i>et al.</i> (2016)
P ₂ O ₅	MJ kg ⁻¹	11.1	
K ₂ O	MJ kg ⁻¹	6.7	
ZnSO ₄	MJ kg ⁻¹	8.4	Bijarniya <i>et al.</i> (2020)
FeSO ₄	MJ kg ⁻¹	110	
Irrigation	ha-cm	143.56	Gathala <i>et al.</i> (2016)
Chemicals			
Pendimethalin	MJ l ⁻¹	120.0	Mittal (1985)
Quizalofop ethyl			
Imidachloprid			
Output			
Main product and by product			
Rice and blackgram	MJ kg ⁻¹	14.7	Mittal (1985)
Rice straw and haulm	MJ kg ⁻¹	12.5	

RDN by VC + AM fungi + foliar nutrients of 0.5% Urea + 1% FeSO_4 + 0.5% ZnSO_4 (S_6) recorded higher output energy (57.4%) and net energy (108405 MJ ha⁻¹) compared to full dose of RDN by inorganic fertilizer (Table 2). Higher grain and straw yield favours higher output energy (Kumar *et al.*, 2015). This increase in energy output correlates directly with the biological yield of the crops (Mallikarjun and Maity, 2017; Singh *et al.*, 2022). The application of organic manures in nutrient management facilitates a gradual and sustained release of nutrients thereby minimizing losses through leaching and volatilization. This controlled nutrient availability enhances nutrient use efficiency, optimizing energy conversion within the cropping system and contributing to higher net energy gain. In contrast, the exclusive application of inorganic fertilizers often results in suboptimal nutrient utilization due to rapid nutrient release, which increases the risk of losses through leaching, denitrification and volatilization. Consequently, the lower efficiency of nutrient uptake in sole inorganic fertilizer treatments leads to reduced energy productivity and a lower net energy balance in the system (Gamaik *et al.*, 2025).

Response on specific energy and energy intensiveness

Rice with *dhaincha* intercropping (M_2) significantly reduced the specific energy (11.1%) as compared to rice alone (M_1). However, there was no significant effect of *dhaincha* intercropping (M_2) on energy intensiveness (Table 2). Among the nutrient management strategies, combined application of inorganic fertilizer, enriched FYM, vermicompost, AM fungi and foliar application of nutrients (S_6) significantly reduced the specific energy (46.1%) and energy intensiveness (35.4%) compared to recommended

dose of fertilizer (S_2). Higher specific energy value was recorded in control plot. It denotes a less efficient cropping system. The lowest specific energy value was observed with *dhaincha* (M_2) intercropping and sustainable nutrient management practices (S_6). Lowest value of specific energy indicate the more efficient cropping system. Energy intensiveness recorded lower values with sustainable nutrient management strategies (S_6). The per unit energy of organic manures was lower compared to chemical fertilizers which lead to lower energy intensiveness as earlier reported by Pooniya *et al.* (2017).

Response on energy productivity and energy use efficiency

Rice with *dhaincha* intercropping significantly increased the energy productivity (0.150 kg MJ⁻¹) and energy use efficiency (9.9%) over sole rice (Table 2). Among the various nutrient management practices, plots treated with half dose of RDN by inorganic fertilizer, quarter dose of RDN by EFYM, quarter dose of RDN by VC, AM fungi and foliar nutrients of 0.5% Urea, 1% FeSO_4 , 0.5% ZnSO_4 (S_6) recorded significantly higher energy productivity (0.200 kg MJ⁻¹) and energy use efficiency (42.9%) than sole application of chemical fertilizer (S_2). The increased energy use efficiency and energy productivity were observed in sustainable nutrient management strategies were indeed a result of higher crop productivity. A judicious combination of organic and inorganic nutrient sources led to a reduction in the use of non-renewable energy inputs. Higher output energy and low input energy recorded in the sustainable nutrient management practices lead to higher energy use efficiency and energy productivity as reported by Meena *et al.* (2021).

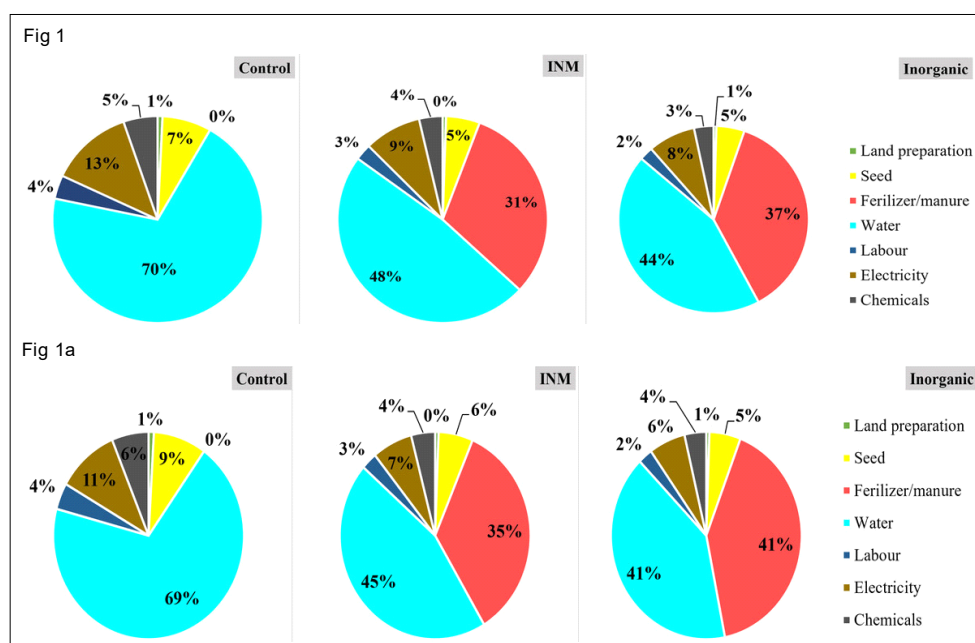


Fig 1: Percentage share of energy from different agricultural inputs (control, inorganic and INM) for sustainable production of aerobic rice-blackgram cropping system during 2022 and 2023 (Fig 1 and 1a).

Response on human energy profitability, energy profitability and energy output efficiency

Rice with *dhaincha* intercropping significantly increased the human energy profitability (5.89 kg MJ⁻¹), energy profitability (3.01) and energy output efficiency (0.272 × 10³ MJ ha⁻¹ day⁻¹) compared to sole rice (M₁) (Table 2a). With regard to nutrient management strategies, the plot supplied with half dose of RDN from inorganic fertilizer, quarter dose of RDN from EFYM, quarter dose of RDN from vermicompost, AM fungi and foliar application of 0.5% Urea,

1% FeSO₄, 0.5% ZnSO₄ (S₆) recorded significantly increased human energy profitability (8.20 kg MJ⁻¹), energy profitability (4.18) and energy output efficiency (0.383 × 10³ MJ ha⁻¹ day⁻¹) compared to sole application of chemical fertilizer (S₂). The higher human energy profitability in the treatments M₂ and S₆ indicated that integrating *dhaincha* intercropping and sustainable nutrient management strategies with rice could able to increase the efficiency of human labor, lead to better energy utilization and higher productivity (Prajapat *et al.*, 2018).

Table 2: Response of sustainable nutrient management strategies on energy indicators in aerobic - blackgram cropping system (Two years of mean).

Treatments	Output energy (MJ ha ⁻¹)	Net energy (MJ ha ⁻¹)	Energy use efficiency (%)	Energy productivity (kg MJ ⁻¹)	Specific energy (MJ kg ⁻¹)	Energy intensiveness (MJ Rs ⁻¹)
Main plot: Intercropping						
M ₁	89387±5294 ^b	65234±4825 ^b	10.63±0.39 ^b	0.139±0.012 ^a	17.65±1.01 ^a	0.71±0.03 ^a
M ₂	99305±5556 ^a	74583±5161 ^a	11.69±0.43 ^a	0.150±0.012 ^a	15.68±0.94 ^b	0.71±0.03 ^a
SEd	2201	1631	0.20	0.003	0.39	0.02
CD (P=0.05)	9472	7018	0.85	0.014	1.67	0.08
Sub plot: Nutrient management strategies						
S ₁	62087±1565 ^d	43878±2209 ^d	9.07±0.19 ^e	0.100±0.001 ^b	22.40±0.62 ^a	0.70±0.03 ^b
S ₂	84612±2942 ^c	56435±2482 ^c	9.77±0.18 ^d	0.100±0.001 ^b	20.27±0.87 ^b	0.93±0.03 ^a
S ₃	84782±3645 ^c	60391±2437 ^c	10.58±0.31 ^c	0.100±0.001 ^b	17.92±0.68 ^c	0.68±0.02 ^b
S ₄	103207±3557 ^b	77333±2690 ^b	12.05±0.40 ^b	0.183±0.017 ^a	14.10±0.56 ^d	0.73±0.02 ^b
S ₅	98181±3967 ^b	74003±2886 ^b	11.53±0.46 ^b	0.183±0.017 ^a	14.38±0.51 ^d	0.60±0.01 ^c
S ₆	133208±3362 ^a	107411±4140 ^a	13.97±0.27 ^a	0.200±0.000 ^a	10.92±0.29 ^e	0.60±0.02 ^c
SEd	3787	3106	0.31	0.006	0.60	0.03
CD (P=0.05)	7899	6478	0.65	0.013	1.24	0.06
M × S	NS	NS	NS	NS	NS	NS

*Note: ± values are standard error (SE) from mean.

Table 2a: Response of sustainable nutrient management strategies on energy indicators in aerobic - blackgram cropping system (Two years of mean).

Treatments	Human energy profitability (kg MJ ⁻¹)	Energy profitability	Energy output efficiency (× 10 ³ MJ ha ⁻¹ day ⁻¹)
Main plot: Intercropping			
M ₁	5.15±0.37 ^b	2.70±0.17 ^b	0.256±0.017 ^b
M ₂	5.89±0.41 ^a	3.01±0.18 ^a	0.272±0.018 ^a
SEd	0.13	0.07	0.004
CD (P=0.05)	0.55	0.29	0.019
Sub plot: Nutrient management strategies			
S ₁	3.13±0.06 ^d	2.42±0.07 ^c	0.200±0.001 ^d
S ₂	4.68±0.21 ^c	2.02±0.05 ^d	0.200±0.001 ^d
S ₃	4.85±0.22 ^c	2.48±0.10 ^c	0.233±0.021 ^{cd}
S ₄	6.30±0.28 ^b	3.00±0.12 ^b	0.300±0.002 ^b
S ₅	5.97±0.22 ^b	3.03±0.13 ^b	0.267±0.021 ^{bc}
S ₆	8.20±0.34 ^a	4.18±0.12 ^a	0.383±0.017 ^a
SEd	0.27	0.12	0.009
CD (P=0.05)	0.56	0.25	0.018
M × S	NS	NS	NS

*Note: ± values are standard error (SE) from mean.

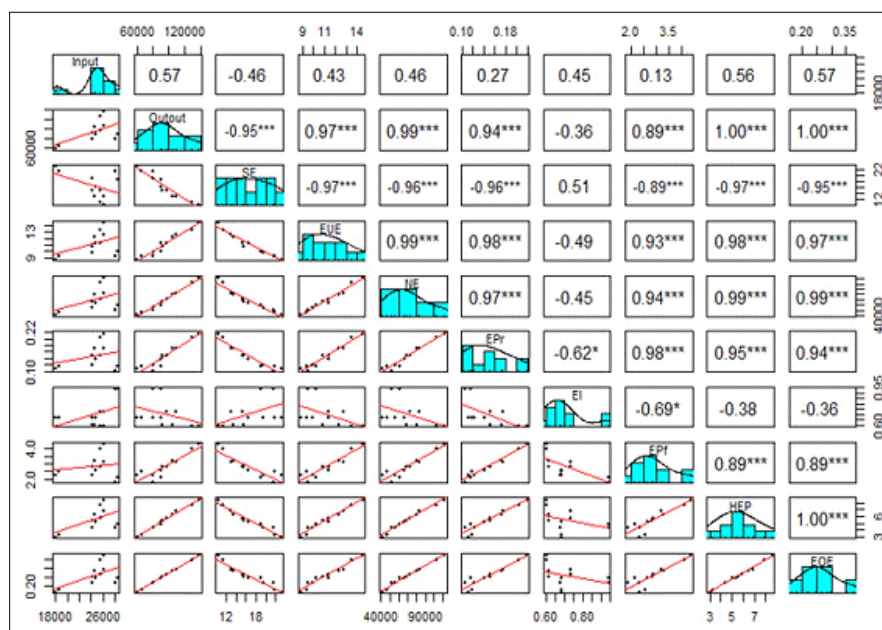


Fig 2: Correlation relationship between energy input and energy indicators in aerobic rice-blackgram cropping system.

With regard to interaction the effect between *dhaincha* intercropping and nutrient management strategies on energy indicators was non-significant.

Correlation analysis

The correlation coefficients indicated significant relationships between the variables (Fig 2). Notably, all inputs demonstrates a strong positive correlation with both output and energy use suggesting that changes in the input variable are closely associated with corresponding changes in output measures. Conversely, variables such as specific energy and energy intensiveness exhibit a moderate negative correlation with input (-0.95 and -0.36, respectively), indicating an inverse relationship. Other variables like energy use efficiency, net energy and human energy profitability showed moderate to strong positive correlations with input reflecting varying degrees of positive associations. Meanwhile, energy productivity and energy profitability demonstrate weaker positive correlations. These results emphasize the importance of optimizing energy inputs to enhance productivity and energy efficiency in the aerobic rice-blackgram system. Variables viz., energy use efficiency and net energy highlight efficient system performance, while human energy profitability demonstrate the contributions of economic energy from labour and total output respectively.

CONCLUSION

In accordance with the results of the present investigation, adoption of sustainable nutrient management strategies viz., green manure, organic manures, inorganic fertilizers, micronutrients and biofertilizer increased the energy use efficiency by 10-43%, energy output by 11-60% and energy profitability while decreasing production cost by 9.10-11.63% compared to the recommended dose of fertilizer in aerobic rice-blackgram cropping system. Therefore, the integrated

nutrient management approach represents a sustainable and practical strategy for enhancing productivity, reducing input costs and ensuring long-term soil health, particularly under the agro-climatic conditions of the Western Zone of Tamil Nadu, India.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

Nil.

Conflict of interest

All authors declare that they have no conflicts of interest.

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