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Effect of Crop Establishment Methods and Microbial Inoculations on Augmenting the Energy Efficiency and Nutritional Status of Rice and Wheat in Cropping System Mode

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Abstract: A field experiment was conducted for two consecutive years with the aim to quantify the role of different nutrient management variables such as microbial inoculation, zinc (Zn) fertilization and optimal and sub-optimal fertilization of nitrogen and phosphorus on the energetic and nutritional status of the rice–wheat cropping system (RWCS). The said nutrient management variables were applied over six different crop establishment methods (CEMs) in RWCS viz. puddled transplanted rice (PTR), system of rice intensification (SRI) and aerobic rice system (ARS) in rice and conventional drill-sown wheat (CDW), system of wheat intensification (SWI) and zero-tillage wheat (ZTW) in wheat. Two microbial consortia viz. *Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia (MC1) and *Anabaena-Pseudomonas* biofilmed formulations (MC2) were used in this study, while recommended dose of nitrogen (N) and phosphorus (P) (RDN) (120 kg N ha^{-1} and 25.8 kg P ha^{-1}), 75% RDN and Zn fertilization (soil applied 5 kg Zn ha^{-1} through zinc sulphate heptahydrate) were the other variables. The contribution of microbial consortia, Zn fertilization and RDN (over 75% RDN) to net energy production of RWCS was 12.9–16.1 $\times$ 10^3 MJ ha^{-1}, 10.1–11.0 $\times$ 10^3 MJ ha^{-1} and 11.7–15.3 $\times$ 10^3 MJ ha^{-1}. Among the CEMs, the highest gross and net energy production was recorded in ARS–ZTW with lowest energy required for production of one tonne of system yield (2366–2523 MJ). The system protein yield varies from 494.1 to 957.7 kg ha^{-1} with highest protein yield in 75% RDN + MC2 + Zn applied ARS–ZTW. Among micronutrients, the uptake of Zn and iron (Fe) is sensitive to all studied variables, while manganese (Mn) and cupper (Cu) uptake was found significantly affected by CEMs alone. The combination of 75% RDN + MC2 + Zn in ARS–ZTW was found superior in all respects with 288.3 and 286.9 MJ ha^{-1} net energy production and 2320 and 2473 MJ energy required for production of one tonne system yield in the first and second year of study, respectively.

Keywords: aerobic rice; energetics; nitrogen; protein yield; system of rice intensification; zero-tillage wheat; zinc

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1. Introduction

Rice and wheat are the forerunner staple food crops in imparting the energy for humans, directly through carbohydrate and protein as the main components of foods and indirectly through different provisional services. Out of the total protein consumption in India, 56.7% is from cereals [1], while 20% of per-capita energy for humans and 13% protein in the diet of nearly half of the world population were contributed by rice, and this share is much higher in developing countries [2]. The share of both crops to food grain production is 75.11%, while the share in total cereal production was 81.3% [3]. This indicates the role of rice and wheat in meeting the protein requirement of the Indian population. On another side, the contribution of rice and wheat to resource utilization among all crops is the highest with 34.5% and 24.4% of the gross cropped area under rice and wheat, respectively [3]. At the same time, the share of rice in the total fertilizer consumption is 37% for nitrogen (6.98 million tonnes), 37% for phosphorus (2.76 million tonnes) and also 37% for potassium (0.977 million tonnes) in 2020–2021, respectively, and the same for wheat was nearly 24% for nitrogen (4.897 million tonnes) and 24% for phosphorus (2.155 million tonnes). Besides the above-mentioned natural resources, the monetary involvement is much higher in the cultivation of both crops with an average cost of cultivation for rice varying from Indian national rupee (INR) 1082.5 to 2732.6 for 100 kg grain yield, and the same for wheat varies from INR 1109.8 to 2233.9 for 100 kg grain yield, respectively [4]. The monetary criteria such as gross and net returns are used most commonly for calculating crop profitability, while for different artificial resources such as irrigation water, electricity, petroleum products, fertilizers, etc., which are purchased at a subsidized price, the present monetary evaluation is not complete. In this regard, the evaluation of all resources in a single unit, and with it the non-subsidized or original cost, is needed, and this can be carried out by the quantification of all inputs and outputs in terms of energetic and nutritional outcome. The need for accounting for energetics in crops and cropping systems along with monetary returns can be justified by increasing energy scarcity, increasing adoption of energy-efficient CEMs [5–7], the contribution of energy to greenhouse gas emissions and subsidies on fertilizers. As energy scarcity is aggravating and large variants for management practices and input additions are available, the study of these parameters for their energy efficiency will be an important scope and generate valuable scientific information. The requirement of energy per kg of crop produce and reduction in energy requirements for different field operations, and higher net energy production with the same level of resources, are useful criteria for judging efficiency in crop production. This high contribution of both crops to input consumption and meeting the energy and nutritional requirements of human beings creates scope to evaluate both crops in the cropping system mode for their energetic and nutritional outcomes.

Rice and wheat had significant variation in the crop establishment methods (CEMs) and cultivation methods and this can be explained by significant variations in hydrological regimes in rice ecosystems in India [8–11] and variation in tillage and land configuration in wheat [7,12]. The significance of energetics in a crop/cropping system has both economic and environmental bias. The largest contribution of the energy sector to global warming [13] with finite, limited and shrinking conventional (coal and petroleum-based) energy resources and increasing emphasis of policy makers on use of solar, wind and hydroelectric energy explain the environmental bias of energetics, while increasing the price per unit of energy leading to increasing prices of inputs, promotion of energy-efficient machines/equipment in crop production [14,15] and increasing wages of labour elucidate the economic bias of energy use. The energy equivalents given by different authors [16–18] indicate the highest energy equivalent per unit input was accounted by different nutrients. The energy equivalent for 1 kg nitrogen, phosphorus, potassium and Zn was 60.6 MJ, 11.1 MJ, 6.7 MJ and 20.2 MJ, respectively. The higher energy equivalent signifies the need for studying nutrient management variables for their role in energetics, while variation in CEMs and cultivation methods leading to variation in tillage requirements create scope for studying their energetics with varied levels of inputs. Along with the energy equivalent, the nutritional status of both crops needs to be studied considering their contribution to human nutrition and growing concerns of micronutrient deficiency [19,20] and other health-related risks [21,22]. The CEMs were studied for their energetics, while scientific information on the interactions of different CEMs and input additions (microbial inoculation, Zn fertilization and optimum and sub-optimum fertilization) on the energetic and nutritional status of RWCS is lacking, which was considered a research gap. Considering the increased number of crop establishment methods (CEMs) in RWCS with significant variations, the significant contribution of both rice and wheat to input consumption and human nutrition and the high energy equivalent of nutrients, the study was planned with two objectives: (i) to identify the energy-efficient CEMs in RWCS and the role of microbial inoculations and Zn fertilization in enhancing the energetics of RWCS; and (ii) to know about the micronutrient uptake in rice and wheat as affected by applied treatments, thereby increasing the nutritional status of grains.

2. Material and Methods

2.1. Experimental Site

The field experiment was conducted consecutively for two years (2013–2014 and 2014–2015) at Research Farm of ICAR-Indian Agricultural Research Institute, New Delhi (latitude of 28°38′ N, longitude of 77°10′ E and altitude of 228.6 m above the mean sea level). Two crops in a year including rice during wet season (June to September) and wheat during dry/winter season (November to April) were grown. The climate of New Delhi is of subtropical and semi-arid type with hot and dry summers followed by monsoon rains in July-September and cold winters in November–April and falls under the agro-climatic zone 'Trans-Gangetic plains'. The mean annual normal rainfall and evaporation are 650 and 850 mm, respectively. Amount of rainfall received during growing duration of first cycle of RWCS (2013–2014) was 1497.4 mm, out of which 1349.8 mm was received during rice growing season and 147.6 mm was received during wheat growing season. In second cycle (2014–2015), total rainfall was 760 mm, out of which 451.4 mm received in rice growing season and 308.6 mm during wheat growing season. The number of rainy days was higher during first rice growing season (39 days) than second rice growing season (22 days). The highest amount of rainfall during rice growing season was received during 33rd (196.1 mm) and 29th meteorological weeks (112.7 mm) in first and second year, while in case of wheat, 7th (53 mm) and 9th (135.4 mm) meteorological weeks received highest rainfall in first and second year, respectively (Supplementary Tables S1 and S2).

The soil was sandy clay loam (Typic Ustochrept) in texture with a mechanical composition [23] of 51.4% sand, 22.2% silt and 26.4% clay. The soils of experimental field had 0.54% organic C [24], 257 kg ha^{-1} alkaline permanganate oxidizable N [25], 17 kg ha^{-1} available P (Olsen's method) [26], 327 kg ha^{-1} 1 N ammonium acetate exchangeable K [27] and 0.85 mg kg^{-1} of available zinc [28]. The pH of the soil was 7.6 (1:2.5 soil-to-water ratio) [29].

2.2. Experimental Details

The field experiment was planned in split-plot design with six crop establishment methods (CEMs) with three for each rice (*Pusa Sugandh 5*) and wheat (*HD 2967*) as main plot (net area for each main plot was 256.5 m^2). The CEMs were arranged as puddled transplanted rice (PTR) followed by (*fb*) conventional drill-sown wheat (CDW), system of rice intensification (SRI) *fb* system of wheat intensification (SWI) and aerobic rice system (ARS) *fb* zero-tillage wheat (ZTW). In all these CEMs, nine subplot treatments were applied (net area for each sub-plot was 9.5 m^2), which include RDN (recommended dose of nutrients) (120 kg ha^{-1} N and 25. 8 kg ha^{-1} P), 75% RDN, 75% RDN + *Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia (MC1) and 75% RDN + *Anabaena-Pseudomonas* biofilmed formulations (MC2). These four treatments were applied with and without Zn (soil applied 5 kg Zn ha^{-1} through zinc sulphate heptahydrate) making total eight treatments and one control (no fertilizer). All treatments were replicated thrice.

2.3. Crop Establishment Methods (CEMs)

The details for CEMs of rice and wheat are mentioned in Tables 1 and 2. In order to have the same crop growth duration in all three methods of cultivation, sowing of rice in main field for ARS and sowing rice in nursery for transplanting in both PTR and SRI was performed on the same date. The PTR is traditionally followed by the CEM in which rice is grown in standing water. The level of standing water is maintained by reduction in soil infiltration rate through soil cultivation in standing water before transplanting (puddling) and applying irrigation at frequent intervals. The level of water is maintained at 2–3 cm during vegetative growth stage and increased up to 5 cm during flowering and grain filling stage. In SRI [30–32], soil puddling is carried out the same as that of PTR and soil water level is maintained at saturation. The seedlings at13–14 days old were transplanted with 1–2 healthy seedlings per hill at a spacing of 20 cm × 20 cm. The ARS is growing of rice in unsaturated, unpuddled and arable soil conditions [33]. The soil is maintained at field capacity and direct sowing of pre-soaked rice grain was conducted through seed-drill. In case of wheat, drill-sowing of wheat is mostly followed in India in which row sowing of seed at 22.5 cm with seed drill is performed, while SWI [34–36] is a new CEM involving dibbling or transplanting of young seedlings at 20 cm × 20 cm spacing. The ZTW is gaining acceptance in Indo-Gangetic plains (IGPs) by the farmers due to energy and cost saving [12] and timely sowing [7].

2.4. Application of Microbial Inoculation and Fertilizers

Two microbial consortia were applied in present study (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia (MC1) and *Anabaena-Pseudomonas* biofilmed formulations (MC1)) [37,38]. For application of microbial consortia, a thick paste of respective culture was made in carboxyl methyl cellulose and applied to rice seedlings in PTR and SRI by dipping roots in paste of respective culture for half an hour before transplanting. In ARS, pre-soaked seeds were treated with thick paste of culture made in carboxyl methyl cellulose half an hour before sowing. In wheat, thick paste of respective culture was made in carboxyl methyl cellulose (CMC) and seeds were treated with this thick paste in all CEMs for half an hour just before sowing. For application of N, P and K chemical fertilizers, urea, single super phosphate and muriate of potash were used, while zinc sulphate heptahydrate was used for supply of Zn. Among nutrients, P, K and Zn were applied at the time of sowing and N was split, applied in both rice and wheat (Tables 1 and 2).

2.5. Energy Calculation

For calculation of gross energy, grain and straw yield was measured and their cited energy equivalents [16,18] were considered. The energy equivalents mentioned in [16–18] were used to calculate the energy input (Table 3). The energy input consists of both direct (human labour, diesel and electricity) and indirect (seed, fertilizers and machinery) energy in rice and wheat. The net energy output is calculated by subtracting energy input from gross energy output. The energy input is also expressed as energy tonne^{-1} of economic yield produced.

2.6. Calculation of Grain Yield, Protein Yield and Micronutrient Uptake

Both rice and wheat were harvested at harvest maturity and threshed produce obtained from net plot areas were cleaned, dried and weighed at 14% moisture content and expressed as Mg ha^{-1}. The protein yield was calculated based on the nitrogen concentration in grain. For determining the nitrogen content, the plant sample (0.5 g each) was digested by using 10 mL of analytical grade concentrated sulphuric acid along with a pinch of digestion mixture ($CuSO_4$ + K_2SO_4) to determine total nitrogen content. The samples were analyzed by using Kjeldahl's apparatus [39] and were expressed as percentage. The zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) concentrations in rice and wheat plant samples were determined as per the procedure described by [40] using Atomic Absorption Spectrophotometer (AAS) and expressed as mg kg^{-1}. For calculating the uptake in grain, grain yield was measured at 12% moisture content. For rice, white rice kernel was used instead of rough rice.

Table 1. The details about methodologies of different CEM in rice.

Method of Cultivation	Method of Sowing	Seed Rate (kg ha^{-1})	Spacing (cm)	Age of Seedling	Seedling hill^{-1}	Land Preparation	Water Management	Number of Irrigation	Depth of Irrigation	Weed Management	Nutrient Application Method and Timing
PTR	Transplanting (manual)	20	20 × 15	23–25 days old	2–3	One ploughing, one harrowing and puddling twice	5 cm water applied at each irrigation; puddled and saturated	11 in first year and 18 in second year	5 cm puddled saturated	Two hand weeding in each crop	Broadcasting; 1/3 at 5 DAT, 1/3 at 25 days after transplanting (DAT) and 1/3 at 55 DAT for N; All dose of P, K and Zn at 5 DAT
SRI	Transplanting (manual)	5	20 × 20	13–14 days old	1	One ploughing, one harrowing and puddling twice	2 cm up to panicle initiation and 5 cm thereafter	11 in first year and 20 in second year	2 cm up to panicle initiation and 5 cm thereafter	Two hand weeding in each crop	Broadcasting; 1/3 at 5 DAT, 1/3 at 25 DAT and 1/3 at 55 DAT for N; All dose of P, K and Zn at 5 DAT
ARS	Direct sowing of seed in main field	60	20 cm row to row	Direct sowing of seed in field	-	One ploughing followed by harrowing	2 cm to maintain field capacity moisture level, non-saturated and non-puddled	10 in first year and 24 in second year	2 cm to maintain field capacity moisture level, non-saturated and non-puddled	Three hand weeding in each crop	Broadcasting; 1/3 at sowing, 1/3 at 30 days after sowing (DAS) and 1/3 at 60 DAS for N; All dose of P, K and Zn at sowing

Table 2. The details about methodologies of different CEMs in wheat.

Method of Cultivation	Method of Sowing	Seed Rate (kg ha^{-1})	Spacing	Land Preparation	Water Management	Weed Management	Nutrient Application Method and Timing
CDW	Sowing through seed drill	100	22.5 cm row to row	One ploughing followed by one harrowing and planking	Four and six irrigations at critical growth stages in first and second year, respectively, in all CEMs	Two hand weeding in each crop at 20 and 40 days after sowing (DAS) in all CEMs	Broadcasting; 1/3 at sowing, 1/3 at 30 DAS and 1/3 at 60 DAS for N; All dose of P, K and Zn at sowing
SWI	Dibbling of seeds (manual)	30	20 cm × 20 cm	One ploughing followed by one harrowing and planking			
ZTW	Sowing through seed drill	120	22.5 cm row to row	Direct sowing without cultivation			

Table 3. Energy equivalents used for calculation of energy input and output in production system [16–18].

S. No.	Input Used	Energy Equivalent (MJ Unit^{-1})
1.	Human labour	1.96
2.	Diesel (per litre)	56.31
3.	Farm machinery	62.7
4.	Fertilizer (Nitrogen MJ kg^{-1} N)	60.60
5.	Fertilizer (Phosphorus MJ kg^{-1} N)	11.2
6.	Fertilizer (Potassium MJ kg^{-1} N)	6.7
7.	Fertilizer (Zinc Sulphate Heptahydrate MJ kg^{-1} N)	20.2
8.	Electricity (per unit)	11.93
9.	Rice and wheat grain (MJ kg^{-1})	14.7
10.	Rice and wheat straw (MJ kg^{-1})	12.5

2.7. Statistical Analysis

The data obtained from the experiment were statistically analyzed using analysis of variance (ANOVA) using the IBM SPSS statistics package and the Duncan's multiple range test to quantify and evaluate the source of variation at the 5% level of significance.

3. Results

3.1. Energy Input

Energy requirement was higher in rice than wheat in both years (Figures 1 and 2). In both crops, the second year had a higher energy requirement than the first year. Among all major operations, fertilization requires higher energy in rice, wheat and the rice–wheat cropping system. The share of fertilizer application in total energy consumption is 54–62%, 66–75% and 59–68% in rice, wheat and RWCS, respectively. The fertilization (54–62%), land preparation (17–22%) and irrigation (8–10%) are the three major consumers of energy in rice. The energy required for nursery, seed and sowing accounts for 10–11% in PTR, 5–6% SRI and 6% in ARS. In wheat, 66–75% of the total energy was accounted for by fertilization. The contribution of land preparation to the total energy consumption was 16–17% in CDW and SWI, while it was zero in ZTW (Figures 1 and 2). The seed requirement was the lowest in SWI and therefore accounts for only 3–4% of total energy. The CDW and ZTW require 11% and 16% energy for seed. In the case of system energy inputs, fertilization, land preparation and irrigation accounts for 59–68%, 9–19% and 6–10% of total energy, respectively. Among all operations, the energy required for nursery, seed requirement, land preparation and fertilization varies across CEMs. The renewable energy (seed and labour) consumption in rice varies from 1257.0 to 1879.7 MJ ha^{-1}, while in wheat it varies from 1258.2 to 2516.6 MJ ha^{-1} (Table 4). The highest renewable energy consumption was observed in ARS and ZTW, while the highest non-renewable energy consumption was recorded in PTR and CDW. In all CEMs of rice, indirect energy accounts for 61.8 to 69.9% of total energy inputs and in wheat its share is 75.9 to 90.7%. In rice, both direct and indirect energy consumption was highest in PTR. In case of wheat, direct energy consumption was highest in SWI, while indirect energy use was highest in ZTW (Table 5). The application of microbial consortia and Zn fertilization require 20 and 101 MJ ha^{-1} energy, while the application of microbial consortia decreases energy requirements by 1964.5 MJ ha^{-1} over RDN (Tables 4 and 5). Among CEMs, PTR had the highest energy requirement and it was higher by 1222–1229 and 2043–2391 MJ ha^{-1}, respectively, than SRI and ARS. In wheat, ZTW reduces the energy requirement by 1655 and 684 MJ ha^{-1} over CDW and SWI. On the system basis, ARS-ZTW was found superior in saving energy.

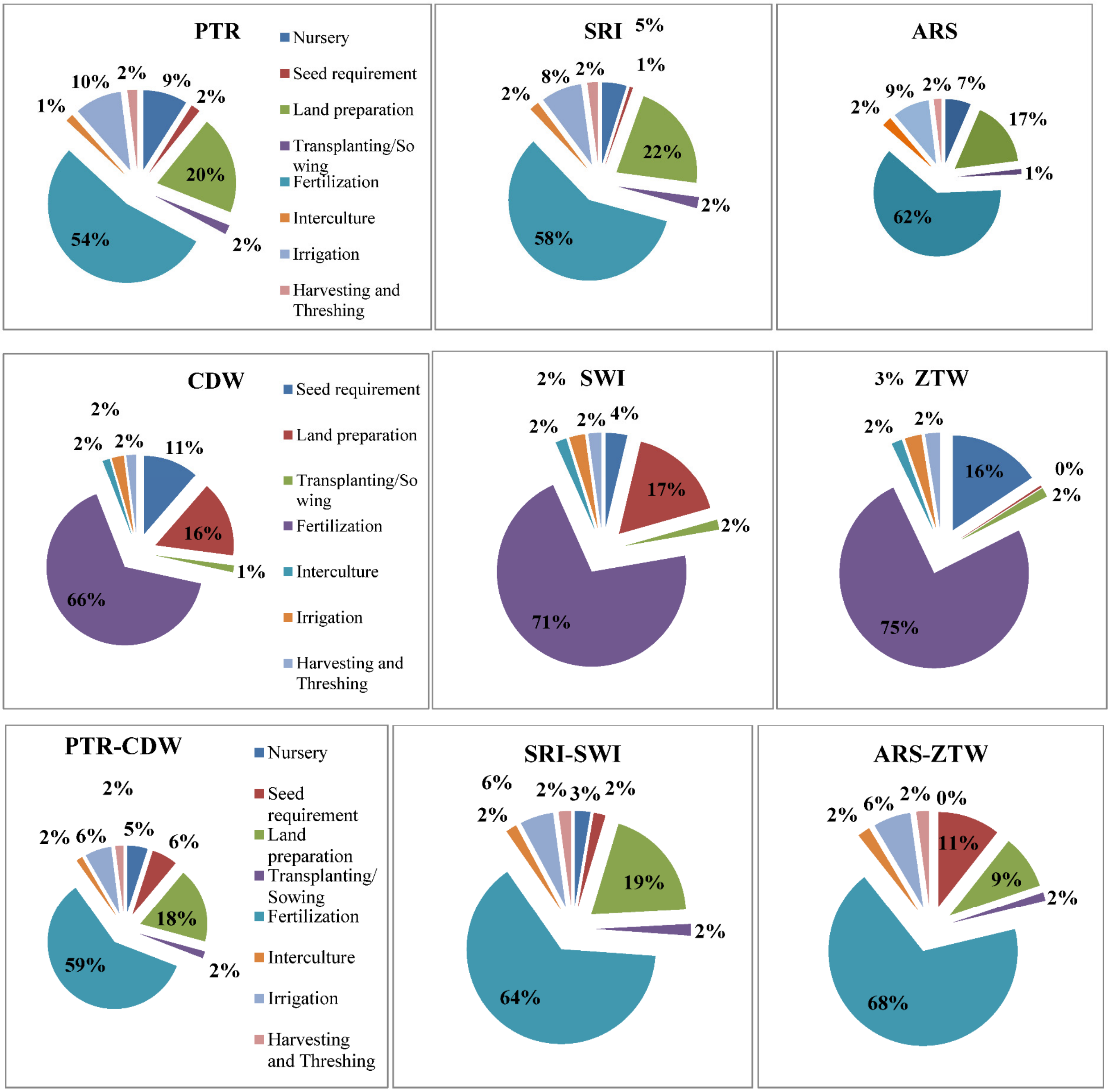


Figure 1. Effect of crop establishment methods on energy requirement for different inputs and operations in rice–wheat cropping system in 2013–2014.

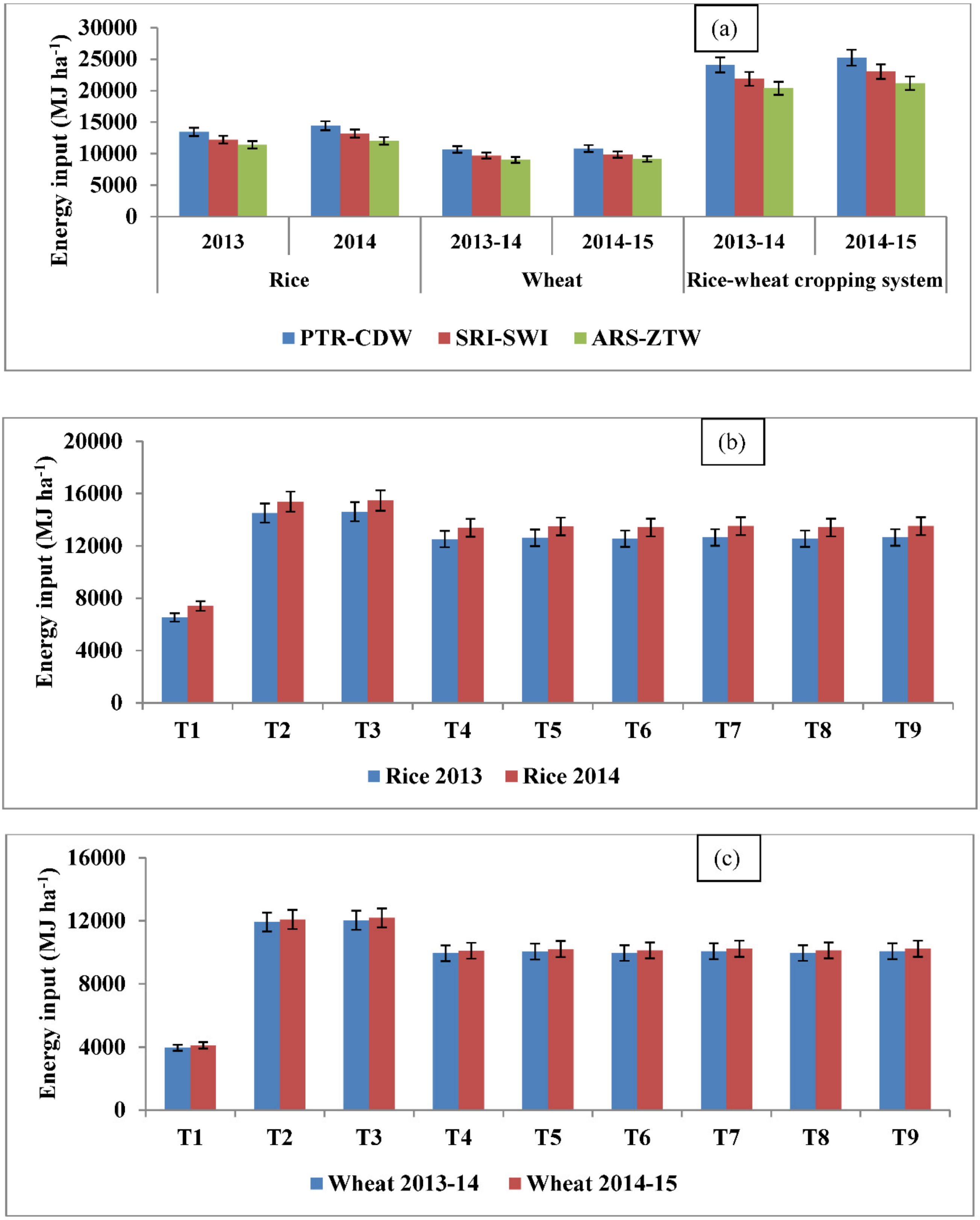


Figure 2. *Cont.*

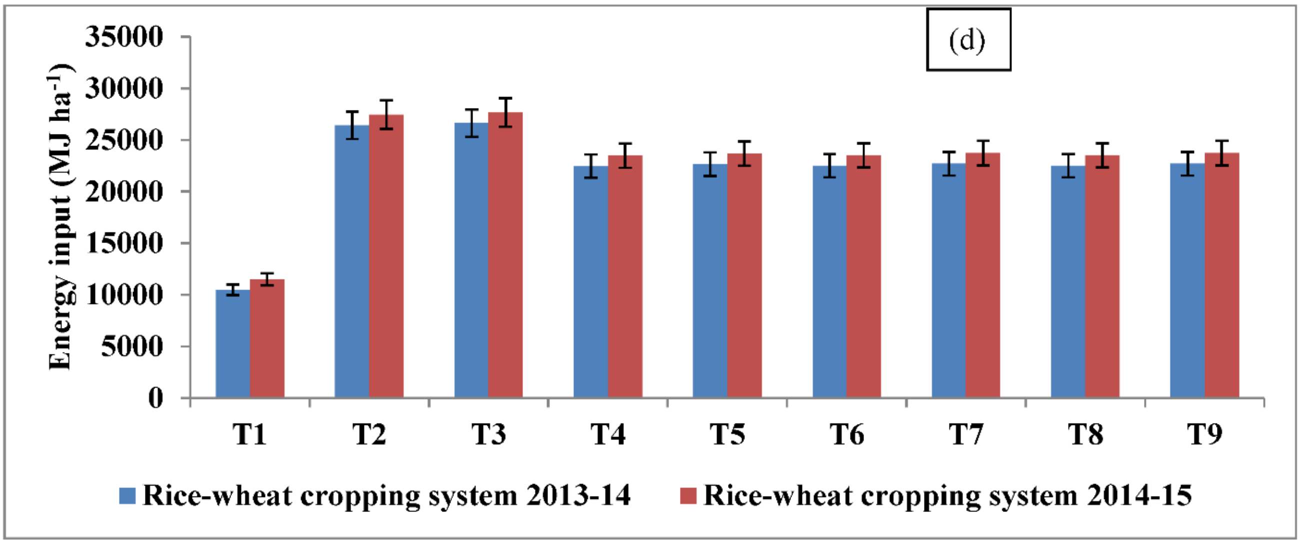


Figure 2. Effect of crop establishment methods (**a**) and nutrient management (**b**–**d**) on energy input requirement in rice–wheat cropping system. (T1: Control, T2: RDN, T3: RDN + Zn, T4: 75% RDN, T5: 75% RDN + Zn, T6: 75% RDN + MC1, T7: 75% RDN + MC1 + Zn, T8: 75% RDN + MC2 and T9: 75% RDN + MC2 + Zn). RDN Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn: Soil applied with 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

3.2. Energy Production

The PTR and SRI were found statistically superior to ARS in gross energy production in both years (Table 6). The net energy production in SRI was significantly higher over both PTR and ARS, while between PTR and ARS, PTR was found superior to ARS. The net energy production in SRI was higher by 1000 to 1500 MJ ha^{-1} over PTR and 4800 to 5100 MJ ha^{-1} over ARS. The lower net energy production in ARS was mainly due to lower yield. The saving in energy per tonne of rough rice produced in ARS was 401–492 and 86–167 MJ t^{-1} more than PTR and SRI. In the case of wheat, both gross and net energy production in ZTW were significantly higher than CDW and SWI. The increase in gross and net energy production in ZTW over CDW was 7500–8000 and 9200–9600 MJ ha^{-1} and similarly for ZTW versus SWI was 8200–8600 and 8900–9300 MJ ha^{-1}, respectively. The ZTW required the lowest amount of energy for production of a tonne of grain. The saving in energy per tonne of grain produced was 216–488 and 274–275 MJ ha^{-1} over CDW and SWI, respectively. The system gross energy output was highest in ARS–ZTW but remained on par with all other CEMs in the first year. During the second year, gross energy production in ARS–ZTW was significantly higher than SRI–SWI and remained on par with PTR–CDW. In regard to net energy production, ARS–ZTW was found superior to both PTR–CDW and SRI–SWI and increased net energy production by 5900 and 4100 MJ ha^{-1}. The energy required to produce a tonne of system yield varied between 2523 and 3039 MJ ha^{-1} and all three systems differed significantly, with ARS–ZTW found superior over the rest.

Table 4. Partitioning of energy inputs in different forms of energy in selected crop establishment methods of rice during first cycle of RWCS.

Particular	Direct Energy (MJ ha^{-1})				Total Direct Energy	Indirect Energy (MJ ha^{-1})				Total Indirect Energy (MJ ha^{-1})	Grand Total (MJ ha^{-1})
	Renewable	Non-Renewable				Renewable	Non-Renewable				
	Human Labour	Diesel	Electricity	Total		Seed	Fertilizers	Machinery	Total		
Energy requirement in puddled transplanted rice (PTR) for RDN + Zn											
Field preparation	139.2	3350.4	-	3350.4	3489.6	-	-	328.9	328.9	328.9	3818.5
Seed and sowing	341	-	-	-	341.0	294	-	-	-	294	635
Fertilization	41.2	-	-	-	41.2	-	9047	-	9047	9047	9088.2
Inter-cultural operation	270.5	-	-	-	270.5	-	-	-	-	-	270.5
Irrigation	173.5	-	1371.9	1371.9	1545.4	-	-	34.02	34.02	34.02	1579.4
Harvesting	305.8	-	-	-	305.8	-	-	-	-	-	305.8
Total	1271.2	3350.4	1371.9	4722.3	5993.5	294	9047	362.9	9409.9	9703.9	15,697.4
Energy requirement in system of rice intensification (SRI) for RDN + Zn											
Field preparation	100.9	3054.8	-	3054.8	3155.7	-	-	299.9	299.9	299.9	3455.6
Seed and sowing	341.0	-	-	-	341.0	88.2	-	-	-	88.2	429.2
Fertilization	41.2	-	-	-	41.2	-	8744	-	8744	8744	8785.2
Inter-cultural operation	270.5	-	-	-	270.5	-	-	-	-	-	270.5
Irrigation	109.4	-	1085.6	1085.6	1195.0	-	-	26.9	26.9	26.9	1221.9
Harvesting	305.8	-	-	-	305.8	-	-	-	-	-	305.8
Total	1168.8	3054.8	1085.6	4140.4	5309.2	88.2	8744	326.8	9070.8	9159	14,468.2
Energy requirement in aerobic rice system (ARS) for RDN + Zn											
Field preparation	101.9	1970.8	-	1970.8	2072.7	-	-	191.2	191.2	191.2	2263.9
Seed and sowing	176.4	-	-	-	176.4	882	-	-	-	882	1058.4
Fertilization	35.28	-	-	-	35.28	-	8441.0	-	8441.0	8441.0	8475.3
Inter-cultural operation	329.3	-	-	-	329.3	-	-	-	-	-	329.3

Table 4. *Cont.*

Particular	Direct Energy (MJ ha^{-1})				Total Direct Energy	Indirect Energy (MJ ha^{-1})				Total Indirect Energy (MJ ha^{-1})	Grand Total (MJ ha^{-1})
	Renewable	Non-Renewable				Renewable	Non-Renewable				
	Human Labour	Diesel	Electricity	Total		Seed	Fertilizers	Machinery	Total		
Irrigation	94.1	-	1145.3	1145.3	1239.4	-	-	28.4	28.4	28.4	1267.8
Harvesting	258.7	-	-	-	258.7	-	-	-	-	-	258.7
Total	995.7	1970.8	1145.3	3116.1	4111.8	882	8441	219.6	8660.6	9542.6	13,654.4

Table 5. Partitioning of energy inputs in different forms of energy in selected crop establishment methods of wheat during first cycle of RWCS.

Particular	Direct Energy				Total Direct Energy	Indirect Energy				Total Indirect Energy	Grand Total
	Renewable	Non-Renewable				Renewable	Non-Renewable				
	Human Labour	Diesel	Electricity	Total		Seed	Fertilizers	Machinery	Total		
Energy requirement in conventional drill-sown wheat (CDW) for RDN + Zn											
Field preparation	76.44	1773.8	-	1773.8	1850.2	-	-	169	169	169	2019.2
Seed and sowing	176.4	-	-	-	176.4	1470	-	-	-	1470	1646.4
Fertilization	35.3	-	-	-	35.3	-	8441	-	8441	8441	8476.3
Inter-cultural operation	188.2	-	-	-	188.2	-	-	-	-	-	188.2
Irrigation	23.5	-	286.3	286.3	309.8	-	-	7.1	7.1	7.1	316.9
Harvesting	258.7	-	-	-	258.7	-	-	-	-	-	258.7
Total	758.5	1773.8	286.3	2060.1	2818.6	1470	8441	176.1	8617.1	10,087.1	12,905.7

Table 5. *Cont.*

Particular	Direct Energy				Total Direct Energy	Indirect Energy				Total Indirect Energy	Grand Total
	Renewable	Non-Renewable				Renewable	Non-Renewable				
	Human Labour	Diesel	Electricity	Total		Seed	Fertilizers	Machinery	Total		
Energy requirement in system of wheat intensification (SWI) for RDN + Zn											
Field preparation	76.4	1773.7	-	1773.7	1850.2	-	-	169	169	169	2019.2
Seed and sowing	199.9	-	-	-	199.9	441	-	-	-	441	640.9
Fertilization	35.3	-	-	-	35.3	-	8441	-	8441	8441	8476.3
Inter-cultural operation	223.4	-	-	-	223.4	-	-	-	-	-	223.4
Irrigation	23.5	-	286.3	286.3	309.8	-	-	7.1	7.1	7.1	316.9
Harvesting	258.7	-	-	-	258.7	-	-	-	-	-	258.7
Total	817.2	1773.7	286.3	2060	2877.3	441	8441	176.1	8617.1	9058.1	11,935.4
Energy requirement in zero-tillage wheat (ZTW) for RDN + Zn											
Field preparation	35.3	-	-	-	35.3	-	-	-	-	-	35.3
Seed and sowing	176.4	-	-	-	176.4	1764	-	-	-	1764	1940.4
Fertilization	35.3	-	-	-	35.3	-	8441	-	-	8441	8476.3
Inter-cultural operation	199.9	-	-	-	199.9	-	-	-	-	-	199.9
Irrigation	23.5	-	286.3	286.3	309.8	-	-	7.1	7.1	7.1	316.9
Harvesting	282.2	-	-	-	282.2	-	-	-	-	-	282.8
Total	752.6	00	286.3	286.3	1038.9	1764	8441	7.1	8448.1	10,212.1	11,251.6

Table 6. Effect of crop establishment methods on energetic and protein yield of rice, wheat and rice–wheat cropping system.

Treatment	Gross Energy ($\times 10^3$ MJ ha^{-1})		Net Energy ($\times 10^3$ MJ ha^{-1})		Energy tonne^{-1} of Grain (MJ tonne^{-1})		Protein Yield (kg ha^{-1})	
	2013	**2014**	**2013**	**2014**	**2013**	**2014**	**2013**	**2014**
Rice								
Puddled transplanted rice (PTR)	151.2a	149.4a	137.8b	134.9b	3276a	3629a	246.5a	229.1a
System of rice intensification (SRI)	151.5a	149.6a	139.2a	136.4a	2961b	3304b	247.3a	229.6a
Aerobic rice system (ARS)	145.5b	143.7b	134.1c	131.6c	2875c	3137c	221.2b	206.0b
Wheat								
Conventional drill-sown wheat (CDW)	140.4b	142.7b	129.8b	131.9b	2421a	2497a	552.3b	535.1b
System of wheat intensification (SWI)	139.8b	142.0b	130.1b	132.2b	2208b	2281b	550.8b	533.1b
Zero-tillage wheat (ZTW)	148.4a	150.2b	139.4a	141.1a	1933c	2007c	639.1a	621.4a
Rice–wheat cropping system								
Puddled transplanted rice (PTR)–conventional drill-sown wheat (CDW)	291.7a	292.1a	267.6b	266.8b	2834a	3039a	798.8b	764.3b
System of rice intensification (SRI)–system of wheat intensification (SWI)	291.3a	291.6a	269.4b	268.6b	2573b	2773b	798.2b	762.7b
Aerobic rice system (ARS)–zero-tillage wheat (ZTW)	293.9a	293.9a	273.5a	272.7a	2366c	2523c	860.2a	827.3a

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test.

The gross energy production in rice was highest in RDN + Zn applied in PTR and found significantly superior over same treatments applied in SRI and ARS in both years (Table 7). Application of 75% RDN + MC1 + Zn and 75% RDN + MC2 + Zn in PTR and SRI remained on par with RDN and found significantly superior over same treatment applied in ARS in first year, while in second year only 75% RDN + MC2 + Zn in SRI was found on par with RDN. The net energy production was highest in 75% RDN + MC2 + Zn in SRI and found superior over same treatment applied in ARS in both years. The net energy production in 75% RDN + MC2 was higher by 900–1000 and 7300–8600 MJ ha^{-1} than RDN and 75% RDN (averaged over all CEMs). Application of MC1 increased net energy production by 6800–8300, 6900–8500 and 7100–8600 MJ ha^{-1}, respectively, in PTR, SRI and ARS. Similarly, increase in net energy production by MC2 was 7100–8400, 7000–8600 and 7500–8800 MJ ha^{-1}, respectively. The zinc fertilization significantly increased gross and net energy production in all CEMs and in all treatments. The increase in gross and net energy production due to Zn fertilization varied between 1600 and 7300 and 1400 and 7100 MJ ha^{-1}, respectively. The lowest amount of energy for production of one tonne of grain was in control. Among CEMs, control in ARS had significantly lower energy per tonne of rice grain produced. Application of MC1 lower energy required per tonne of grain produced by 167–233 MJ tonne^{-1} and MC2 by 183 to 234 MJ tonne^{-1} over 75% RDN.

Table 7. Effect of nutrient management options on energetic and protein yield of rice in different crop establishment methods.

Treatment	Gross Energy ($\times 10^3$ MJ ha^{-1})		Net Energy ($\times 10^3$ MJ ha^{-1})		Energy tonne^{-1} of Grain (MJ tonne^{-1})		Protein Yield (kg ha^{-1})	
	2013	**2014**	**2013**	**2014**	**2013**	**2014**	**2013**	**2014**
Puddled transplanted rice (PTR)								
Control	129.6j	127.0j	121.9l	118.4p	2395l	2842j	161.0j	144.2i
RDN *	154.3cd	152.0d	138.7efg	135.5ghij	3704a	4089a	258.2de	240.3d
RDN + Zn **	160.4a	159.3a	144.7ab	142.6a	3604ab	3897b	292.6a	274.9a
75% RDN	144.9h	144.0gh	131.3i	129.4m	3515bc	3825bc	215.5gh	202.7f
75% RDN + Zn	149.3f	147.2e	135.6h	132.5kl	3402cd	3783c	220.4fgh	204.5ef
75% RDN + MC1	153.2d	150.8d	139.6def	136.2fghi	3262efg	3642d	258.2de	235.3d
75% RDN + MC1 + Zn	157.8ab	156.3b	144.1abc	141.6abc	3167gh	3476e	283.3ab	267.6ab
75% RDN + MC2	153.3d	151.2d	139.7def	136.5efgh	3262efg	3623d	254.6de	235.1d
75% RDN + MC2 + Zn	158.1ab	156.6b	144.4ab	141.9ab	3174gh	3487e	274.6bcd	257.7bc
System of rice intensification (SRI)								
Control	131.4j	128.7j	125.0k	121.3o	1881m	2293k	172.6j	155.5i
RDN *	154.9cd	152.6d	140.6dc	137.3defg	3421cd	3797bc	259.8cde	241.8d
RDN + Zn **	156.5bc	155.4bc	142.0bcd	139.9bcd	3324def	3613d	290.7ab	273.1a
75% RDN	145.3gh	144.5fg	132.9i	131.1lm	3202fgh	3510e	208.8ghi	196.4fg
75% RDN + Zn	150.0ef	147.8e	137.5fgh	134.4hijk	3096hi	3467e	222.1fg	206.2ef
75% RDN + MC1	153.8cd	151.4d	141.4cde	138.0defg	2972j	3342f	255.6de	232.9d
75% RDN + MC1 + Zn	158.3ab	156.8b	145.8a	143.3a	2894jk	3199gh	276.4abc	257.3bc
75% RDN + MC2	153.9cd	151.8d	141.5cde	138.4def	2979ij	3333f	253.0de	233.6d
75% RDN + MC2 + Zn	159.0ab	157.4ab	146.5a	143.9a	2876jk	3181gh	286.9ab	269.5ab
Aerobic rice system (ARS)								
Control	122.0k	119.3k	116.4m	113.1q	1737n	2049l	154.1k	138.5j
RDN *	149.2f	146.9ef	135.7h	132.8kl	3341de	3637d	232.8f	216.1e
RDN + Zn **	154.6cd	153.5cd	140.9de	139.2cde	3269efg	3484e	261.9cde	245.5cd
75% RDN	139.1i	138.3i	127.6j	126.1n	3118h	3340f	193.0i	181.2h
75% RDN + Zn	143.8h	141.7h	132.2i	129.4m	2996ij	3282fg	204.2hi	189.1gh
75% RDN + MC1	147.8fg	145.4efg	136.2gh	133.2jkl	2900jk	3191gh	218.5fgh	198.1fg
75% RDN + MC1 + Zn	152.4de	150.9d	140.7de	138.6def	2810k	3037i	251.0de	243.3d
75% RDN + MC2	148.0f	145.9efg	136.4gh	133.6ijkl	2894jk	3168h	220.9fgh	203.3ef
75% RDN + MC2 + Zn	152.6de	151.1d	140.9de	138.7def	2814k	3045i	254.5de	238.5d
Nutrient management	*	*	*	*	*	*	*	*
Interaction	*	*	*	*	*	*	*	*

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. "*": Indicates significant different of treatments the 0.05 level of probability by the Duncan's multiple range test; RDN *: Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn **: Soil applied 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

In wheat, the highest amount of gross energy production was recorded in RDN + Zn in ZTW and remained on par with 75% RDN + MC1 + Zn and 75% RDN + MC2 + Zn in ZTW

(Table 8). These three treatments were found significantly superior over same treatment applied in CDW and SWI except RDN in CDW. The net energy production in second year was 100 to 3500 MJ ha^{-1} higher than first year. The application of 75% RDN + MC2 + Zn had the highest net energy production. Application of MC1 and MC2 increases net energy production by 5500 to 6700 and 6800 to 7700 MJ ha^{-1}. Similarly increase in net energy production due to Zn fertilization was 1200 to 7900 MJ ha^{-1}. The energy per tonne of wheat grain produced varied between 786 and 2858 MJ $tonne^{-1}$ in the first year and 853 and 2956 MJ $tonne^{-1}$ in the second year. Application of microbial consortia significantly reduces energy required for production of one tonne of wheat grain, while Zn fertilization found statistically superior when applied with RDN in CDW during both the years and 75% RDN + MC1 in CDW and SWI in first year. The system gross and net energy production varied between 247.2 and 311.9 × 10^3 MJ ha^{-1} and 233.6 and 288.3 × 10^3 MJ ha^{-1} (Table 9). The highest gross and net energy production was found with RDN + Zn in ZTW and 75% RDN + MC2 + Zn in ZTW, respectively. The increase in system net returns due to microbial consortia and Zn fertilization was 12,900 to 16,100 and 4800 to 12,040 MJ ha^{-1}, respectively.

Table 8. Effect of nutrient management options on energetic and protein yield of wheat in different crop establishment methods.

Treatment	**Gross Energy (×10^3 MJ ha^{-1})**		**Net Energy (×10^3 MJ ha^{-1})**		**Energy $tonne^{-1}$ of Grain (MJ $tonne^{-1}$)**		**Protein Yield (kg ha^{-1})**	
	2013–2014	**2014–2015**	**2013–2014**	**2014–2015**	**2013–2014**	**2014–2015**	**2013–2014**	**2014–2015**
Conventional drill–wheat (CDW)								
Control	119.9l	120.2m	115.1i	115.2i	1358m	1439m	340.7h	312.6k
RDN *	143.8defgh	145.5defghi	131.0defg	132.5efgh	2858a	2956a	583.3de	561.5fg
RDN + Zn **	150.0abcde	151.4abcdef	137.1cde	138.3cde	2756b	2858b	647.8b	624.9bcd
75% RDN	134.3jk	138.0jkl	123.5gh	127.1h	2590c	2643d	498.5f	486.7i
75% RDN + Zn	135.6ijk	139.4ijkl	124.7fgh	128.3gh	2589c	2641d	503.3f	496.2hi
75% RDN + MC1	141.0fghijk	144.3fghij	130.1efg	133.3efgh	2469d	2528e	560.5e	546.0g
75% RDN + MC1 + Zn	148.7cdefg	150.2cdefg	137.8cde	139.2cde	2360efg	2449efg	633.4bc	612.0bcde
75% RDN + MC2	142.1efghij	145.3defghi	131.2defg	134.3defg	2450de	2510ef	565.8e	555.9g
75% RDN + MC2 + Zn	148.6cdefg	149.9cdef	137.6cde	138.8cde	2360efg	2453efg	637.8b	620.4bcd
System of wheat intensification (SWI)								
Control	123.8l	124.2m	119.9hi	120.2i	1028n	1103n	355.3h	326.0k
RDN *	143.0defghi	144.6efghij	131.2defg	132.7efgh	2656c	2750c	580.1e	557.9g
RDN + Zn **	148.5cdefg	149.7cdefgh	136.5cde	137.7cde	2575c	2675cd	642.8b	619.4bcd
75% RDN	133.3k	137.0kl	123.4gh	127.0h	2376ef	2428fg	497.0f	484.8i
75% RDN + Zn	135.4ijk	139.2ijkl	125.5fgh	129.1gh	2362efg	2413gh	505.0f	497.5hi
75% RDN + MC1	139.3hijk	142.6hijk	129.4efg	132.5efgh	2275gh	2333hij	554.7e	539.7gh
75% RDN + MC1 + Zn	147.2defgh	148.7defgh	137.3cde	138.6cde	2172i	2258j	628.9bcd	607.0bcdef
75% RDN + MC2	140.6ghijk	143.8ghijk	130.7defg	133.8defgh	2254hi	2312ij	560.8e	550.5g
75% RDN + MC2 + Zn	147.2defgh	148.5defgh	137.3cde	138.4cde	2170i	2260j	632.8bc	615.0bcde
Zero-tillage wheat (ZTW)								
Control	133.2k	133.3l	130.1efg	130.0fgh	786o	853o	436.3g	405.5j
RDN *	150.8abcd	152.1abcd	139.7abc	140.7bcd	2373ef	2466efg	666.1b	643.6bc
RDN + Zn **	157.3a	158.2a	146.1ab	146.8ab	2291fgh	2388ghi	737.2a	713.4a
75% RDN	141.5fghij	144.8defghij	132.3cdef	135.5cdefg	2082j	2139k	583.0de	571.3efg

Table 8. *Cont.*

Treatment	Gross Energy ($\times 10^3$ MJ ha^{-1})		Net Energy ($\times 10^3$ MJ ha^{-1})		Energy tonne^{-1} of Grain (MJ tonne^{-1})		Protein Yield (kg ha^{-1})	
	2013–2014	2014–2015	2013–2014	2014–2015	2013–2014	2014–2015	2013–2014	2014–2015
75% RDN + Zn	143.0defghi	146.4defghi	133.8cde	137.0cdef	2083j	2139k	589.2cde	582.5defg
75% RDN + MC1	148.2cdefg	151.1bcdefg	139.0bcd	141.7abc	1991k	2052l	642.6b	628.1bc
75% RDN + MC1 + Zn	155.6abc	156.7abc	146.3ab	147.2ab	1914kl	1998l	719.8a	697.7a
75% RDN + MC2	148.9bcdef	151.8abcde	139.7abc	142.4abc	1980kl	2042l	647.0b	637.3bc
75% RDN + MC2 + Zn	156.6ab	157.6ab	147.3a	148.1ab	1900l	1986l	730.8a	712.8a
LSD (p= 0.05)	4.05	3.58	4.05	3.58	48.4	45.4	47.6	45.5
Nutrient management	*	*	*	*	*	*	*	*
Interaction	*	*	*	*	*	*	*	*

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. "*": Indicates significant different of treatments the 0.05 level of probability by the Duncan's multiple range test; RDN *: Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn **: Soil applied with 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

Table 9. Effect of nutrient management options on energetic and protein yield of rice–wheat cropping system in different crop establishment methods.

Treatment	Gross Energy ($\times 10^3$ MJ ha^{-1})		Net Energy ($\times 10^3$ MJ ha^{-1})		Energy tonne^{-1} of Grain (MJ tonne^{-1})		Protein Yield (kg ha^{-1})	
	2013	2014	2013	2014	2013	2014	2013–2014	2014–2015
PTR–CDW								
Control	249.5k	247.2g	237.0j	233.6l	1847k	2092o	501.7l	456.7m
RDN *	298.2cdef	297.5c	269.8def	268.0fghi	3268a	3500a	841.5fgh	801.8ghi
RDN + Zn **	310.4a	310.7a	281.8abc	280.9abc	3164b	3360b	940.5abcd	899.9bcd
75% RDN	279.2j	282.1f	254.7h	256.5j	3035c	3209cd	714.0j	689.5k
75% RDN + Zn	284.9ij	286.6f	260.3gh	260.8ij	2986c	3190cd	723.6ij	700.7jk
75% RDN + MC1	294.2fgh	295.1cd	269.7def	269.5efgh	2856de	3063ef	818.7ghi	781.3hi
75% RDN + MC1 + Zn	306.5abc	306.6a	281.8abc	280.8abc	2750efg	2945ghi	916.7cde	879.6def
75% RDN + MC2	295.4fg	296.5c	270.9def	270.9defgh	2844def	3043efg	820.3ghi	791.0ghi
75% RDN + MC2 + Zn	306.7abc	306.5a	282.0abc	280.7abc	2753efg	2952ghi	912.4cde	878.1def
SRI–SWI								
Control	255.2k	252.9g	244.9ij	241.5k	1433l	1662p	527.9l	481.5m
RDN *	297.9cdef	297.3c	271.7def	269.9defgh	3027c	3254c	839.9fhg	799.7ghi
RDN + Zn **	304.9abcde	305.1ab	278.5bcd	277.6bcd	2938cd	3131de	933.6bcd	892.5cde
75% RDN	278.6j	281.4f	256.3h	258.1j	2775efg	2947ghi	705.8j	681.2k
75% RDN + Zn	285.4hij	287.0ef	263.0fgh	263.4hij	2721g	2920hi	727.1ij	703.6jk
75% RDN + MC1	293.1fghi	294.0cde	270.8def	270.5defgh	2617h	2820j	810.3ghi	772.7hi
75% RDN + MC1 + Zn	305.5cdef	305.5ab	283.0abc	281.9ab	2522h	2714kl	905.4de	864.3def
75% RDN + MC2	294.5fg	295.6c	272.2def	272.2defg	2607h	2803jk	813.8ghi	784.1hi
75% RDN + MC2 + Zn	306.2abcd	305.9ab	283.7abc	282.3ab	2514hi	2708kl	919.7cde	884.5def

Table 9. *Cont.*

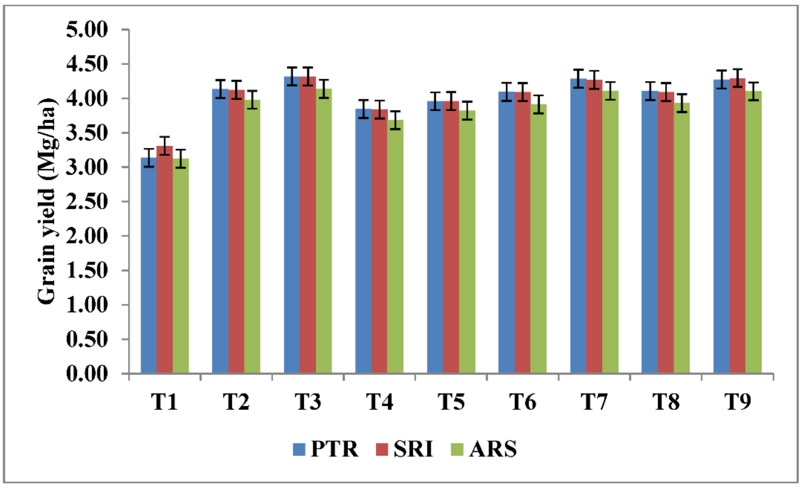
Treatment	Gross Energy ($\times 10^3$ MJ ha^{-1})		Net Energy ($\times 10^3$ MJ ha^{-1})		Energy tonne^{-1} of Grain (MJ tonne^{-1})		Protein Yield (kg ha^{-1})	
	2013	2014	2013	2014	2013	2014	2013–2014	2014–2015
ARS–ZTW								
Control	255.2k	252.6g	246.5i	243.1k	1207m	1376q	590.4k	544.1l
RDN *	300.1bcdef	299.0bc	275.4cde	273.5cdefg	2821efg	3005fgh	898.9def	859.7defg
RDN + Zn **	311.9a	311.7a	287.0ab	286.0a	2740fg	2894j	999.1a	958.9a
75% RDN	280.6j	283.1f	259.9gh	261.6ij	2556h	2687l	776.0i	752.5ij
75% RDN + Zn	286.9ghij	288.1def	265.9efg	266.4ghi	2509hi	2664m	793.4h	771.6hi
75% RDN + MC1	296.0def	296.5c	275.2cde	274.9bcdef	2413ij	2572n	861.1efg	826.2fgh
75% RDN + MC1 + Zn	308.0ab	307.6a	287.0ab	285.9a	2328j	2478n	970.9abc	941.0abc
75% RDN + MC2	296.9def	297.6c	276.2cd	276.1bcde	2404j	2557n	867.9efg	840.5efg
75% RDN + MC2 + Zn	309.2ab	308.7a	288.3a	286.9a	2320j	2473n	985.3ab	951.4ab
LSD (p = 0.05)	4.77	3.93	4.77	3.93	58.6	54.2	61.3	55.7
Nutrient management	*	*	*	*	*	*	*	*
Interaction	*	*	*	*	*	*	*	*

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. "*": Indicates significant different of treatments the 0.05 level of probability by the Duncan's multiple range test; RDN *: Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn **: Soil applied with 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

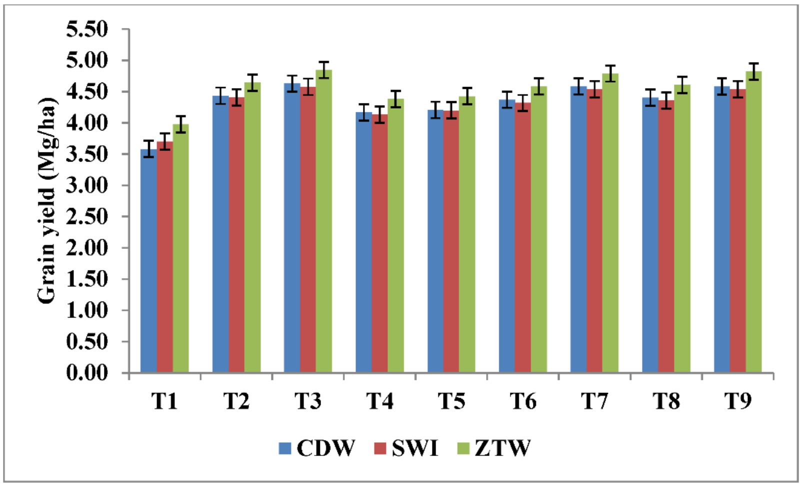
3.3. Grain Yield, Protein Yield and Micronutrient Uptake

The grain yield was significantly affected at the individual crop level, while at system level it remained on par (Figure 3). Application of RDN + Zn recorded the highest yield in both crops, while the yield in 75% RDN + MC1 + Zn and 75% RDN + MC2 + Zn remained on par with RDN + Zn. The protein yield in wheat was higher than rice and this amount is 303 to 318 kg ha^{-1} in the first year and 304 to 315 kg ha^{-1} during the second year (Tables 6 and 7). The system protein yield varied between 456.7 and 999.1 kg ha^{-1}, respectively, with the highest and lowest in RDN + Zn in ARS–ZTW and control in CDW–PTR, respectively (Table 8). In both rice and wheat, CEMs differed significantly in protein production with the highest protein in SRI in rice and ZTW in wheat. The increase in protein yield in PTR over ARS was 25.2 to 23.2 kg ha^{-1}, while the same for ZTW over CDW and SWI was 86.2 to 88.3 kg ha^{-1}. The order of significance for the variation in system protein yield was RDN > microbial consortia > Zn fertilization > CEMs, while their contribution to protein yield was 112.7–326.3 kg ha^{-1}; 85.7–102.1 kg ha^{-1}, 16.1–105.1 kg ha^{-1} and 62–65 kg ha^{-1}, respectively.

The uptake of all studied micronutrients was affected significantly due to CEMs in both rice (white rice kernel) and wheat (whole grain) (Tables 10–12). In rice, PTR and SRI remained on par with each other and were found statistically superior to ARS for all micronutrients. In wheat, ZTW recorded significantly higher micronutrient uptake than both CDW and SWI. Among nutrient management treatments, the uptake of Zn and Fe was significantly affected due to all treatment variables, while for Mn and Cu, the uptake remained on par in all treatments except control. The highest uptake of Zn, Fe, Mn and Cu in rice was 45.42 g ha^{-1}, 235.0 g ha^{-1}, 24.78 g ha^{-1} and 19.66 g ha^{-1} (all in SRI), respectively. Similarly, for wheat it was 217.9 g ha^{-1} for Zn, 528.2 g ha^{-1} for Fe, 179.9 g ha^{-1} for Mn and 35.84 g ha^{-1} for Cu (all in ZTW), respectively.



(**a**)



(**b**)

Figure 3. Effect of crop establishment methods and nutrient management on grain yield of rice (**a**) and wheat (**b**) (pooled data over two years). (T1: Control, T2: RDN, T3: RDN + Zn, T4: 75% RDN, T5: 75% RDN + Zn, T6: 75% RDN + MC1, T7: 75% RDN + MC1 + Zn, T8: 75% RDN + MC2 and T9: 75% RDN + MC2 + Zn). RDN Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn: Soil applied with 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

Table 10. Effect of crop establishment methods on micronutrient uptake in rice and wheat.

Treatment	Zn Uptake (g ha^{-1})		Fe Uptake (g ha^{-1})		Cu Uptake (g ha^{-1})		Mn Uptake (g ha^{-1})	
	2013	2014	2013	2014	2013	2014	2013	2014
Rice								
Puddled transplanted rice (PTR)	38.3a	30.2a	206.0a	184.9a	17.0a	12.5a	21.4a	17.1a
System of rice intensification (SRI)	38.8a	30.3a	208.1a	187.8a	17.1a	12.8a	21.5a	17.2a
Aerobic rice system (ARS)	32.8b	25.8b	182.5b	165.3b	13.8b	10.1b	18.0a	15.1b
LSD (p = 0.05)	0.55	0.45	3.09	4.86	0.80	0.70	0.57	0.63
Wheat								
Conventional drill-sown wheat (CDW)	154.5b	138.1b	418.7b	400.6b	21.6b	18.5b	126.3b	115.2b
System of wheat intensification (SWI)	154.3b	138.7b	418.3b	401.2b	22.2b	18.9b	127.1b	116.3b
Zero-tillage wheat (ZTW)	183.6a	167.1a	475.8a	451.0a	31.1a	26.8a	155.1a	143.4a
LSD (p = 0.05)	1.96	1.82	8.93	7.74	1.88	1.67	5.07	4.90

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test.

Table 11. Effect of nutrient management options on micronutrient uptake in rice in different crop establishment methods.

Treatment	Zn Uptake (g ha^{-1})		Fe Uptake (g ha^{-1})		Cu Uptake (g ha^{-1})		Mn Uptake (g ha^{-1})	
	2013	2014	2013	2014	2013	2014	2013–2014	2014–2015
PTR–CDW								
Control	18.94k	15.15o	133.3kl	113.7n	5.70k	4.23j	9.18l	6.69j
RDN *	40.66cd	31.77ef	216.1cd	194.7def	18.35abc	13.49abcde	22.86abcde	18.29abcde
RDN + Zn **	42.22ab	35.96a	232.2a	210.5ab	19.89a	14.95a	25.03a	20.15a
75% RDN	34.22gh	27.05ij	189.6fgh	171.9hij	15.95efgh	12.04cdefg	20.26efghi	16.31efghi
75% RDN + Zn	35.67fg	27.72i	194.0fgh	175.0hi	16.19defgh	11.69efg	20.44defgh	16.21efghi
75% RDN + MC1	41.32c	32.61de	219.5bc	195.6def	18.97abc	13.91ab	23.51abcd	18.81abcd
75% RDN + MC1 + Zn	44.58ab	35.40ab	228.2ab	207.1abc	19.89a	14.57a	24.54ab	20.01ab
75% RDN + MC2	40.60c	32.20ef	217.0bcd	194.9def	18.49abc	13.56abcd	23.21abcd	18.44abcde
75% RDN + MC2 + Zn	43.55b	33.84cd	223.8abc	200.6cd	19.14ab	14.01ab	23.66abcd	18.98abcd
SRI–SWI								
Control	20.7k	16.44n	144.1k	124.5m	6.74k	5.16j	10.19l	7.45j
RDN *	41.11cd	31.85ef	219.4bc	199.1cd	18.26abcd	13.63abcd	22.95abcde	18.34abcde
RDN + Zn **	45.15ab	35.63a	231.9a	211.7a	19.66a	15.03a	24.78ab	19.93ab
75% RDN	33.45h	26.22jk	184.5hi	168.5ij	15.52ghi	11.95defg	19.69ghijk	15.84fghi
75% RDN + Zn	37.67e	29.31h	197.8efg	179.8gh	17.80abcdef	13.43abcde	22.08bcdefg	17.73bcdefg
75% RDN + MC1	41.03cd	32.09ef	218.8bc	196.3de	18.54abc	13.80abc	23.05abcd	18.40abcde
75% RDN + MC1 + Zn	43.92ab	34.15bc	224.1abc	201.8bcd	19.51a	14.27ab	24.06abcd	19.34abc
75% RDN + MC2	40.38c	31.72ef	217.1bcd	196.4de	18.04abcde	13.41abcde	22.76abcdef	18.02abcdef
75% RDN + MC2 + Zn	45.42a	35.00abc	235.0a	212.5a	19.54a	14.48a	24.28abc	19.43abc
ARS–ZTW								
Control	16.86l	13.54p	123.5l	106.1n	5.02k	3.65j	8.19l	6.49j
RDN *	35.76fg	27.84i	194.3fgh	176.1hi	15.72fgh	11.43fg	20.05fghij	16.79defgh
RDN + Zn **	39.41d	31.25efg	206.2de	188.0efg	16.86cdefg	12.56bcdef	21.67cdefg	18.23abcde
75% RDN	28.45j	22.73m	166.1j	151.5l	12.99j	9.64hi	16.99k	14.29i
75% RDN + Zn	31.01i	23.91lm	175.6ij	159.4kl	13.36j	9.39i	17.45jk	14.44i
75% RDN + MC1	32.44hi	25.24kl	183.6hi	164.2jk	13.58ij	9.49i	17.63ijk	14.55hi
75% RDN + MC1 + Zn	37.38ef	30.25gh	199.7ef	187.3fg	15.61fghi	11.36fgh	19.93ghij	17.36cdefg
75% RDN + MC2	33.61h	26.45ijk	187.2gh	168.9ij	14.48hij	10.33ghi	18.80hijk	15.52ghi
75% RDN + MC2 + Zn	39.74cd	30.84fg	206.0de	185.9g	17.25bcdefg	12.59bcdef	21.63cdefg	18.21abcde
LSD (p = 0.05)	1.84	1.45	11.4	8.7	2.13	1.83	2.73	2.32
Nutrient management treatments	*	*	*	*	*	*	*	*
Interactions	*	*	*	*	*	*	*	*

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. "*": Indicates significant different of treatments at the 0.05 level of probability by the Duncan's multiple range test; RDN *: Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn **: Soil applied with 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

Table 12. Effect of nutrient management options on micronutrient uptake in wheat in different crop establishment methods.

Treatment	Zn Uptake (g ha^{-1})		Fe Uptake (g ha^{-1})		Cu Uptake (g ha^{-1})		Mn Uptake (g ha^{-1})	
	2013–2014	2014–2015	2013–2014	2014–2015	2013–2014	2014–2015	2013–2014	2014–2015
PTR–CDW								
Control	81.6k	70.5k	263.9k	249.0j	61.5j	55.4h	12.5j	10.4j
RDN *	163.0fgh	145.1g	442.3fg	422.4efgh	137.9fg	125.1cd	23.1fgh	19.9fgh
RDN + Zn **	186.1cde	163.4d	469.8de	446.1d	148.7ef	133.9cd	25.0def	21.5de
75% RDN	173.3i	127.8i	394.0b	381.4i	114.3h	106.8f	19.9hi	17.2gh
75% RDN + Zn	140.1i	128.9i	401.9h	386.7i	115.2h	107.3f	19.9hi	16.7hi
75% RDN + MC1	158.8gh	142.2gh	432.0g	416.8h	133.8g	122.8cd	22.7fgh	19.4fgh
75% RDN + MC1 + Zn	181.1e	160.2def	463.7ef	441.4de	144.4fg	130.1cd	24.3defgh	21.4def
75% RDN + MC2	160.1gh	143.7g	435.8g	420.7fgh	136.1g	123.7cd	22.9fgh	19.1fh
75% RDN + MC2 + Zn	182.8de	161.2de	465.1e	441.3de	145.3fg	131.6cd	24.2efgh	21.3defg
SRI–SWI								
Control	86.5k	75.6k	273.3j	258.9j	66.3j	60.4h	15.5i	13.0ij
RDN *	162.0fgh	145.1g	442.9fg	423.9efgh	137.9fg	125.6cd	23.0fgh	19.5fgh
RDN + Zn **	184.5de	162.8d	467.3e	444.7d	148.3ef	134.0c	25.0def	21.4def
75% RDN	136.8i	128.2i	394.7h	383.0i	114.8h	107.7f	20.2gh	17.4fgh
75% RDN + Zn	142.7i	132.3i	403.8h	389.5i	118.7h	111.1ef	22.6fgh	19.3fgh
75% RDN + MC1	156.9h	141.3gh	429.1g	414.8h	133.2g	122.5de	22.4fgh	18.9fgh
75% RDN + MC1 + Zn	179.9e	160.1def	458.8e	437.7defg	144.5fg	130.6cd	24.7defg	21.5ef
75% RDN + MC2	158.3gh	142.9g	433.6g	419.5gh	135.4g	123.4cd	22.5fgh	18.5fgh
75% RDN + MC2 + Zn	180.8e	160.3def	461.6ef	438.8def	144.5fg	131.3cd	23.7fgh	20.5efgh
ARS–ZTW								
Control	111.6j	99.8j	320.8i	299.8i	90.5i	83.4g	23.2fgh	19.7fhg
RDN *	192.6c	174.6c	501.3bc	474.5bc	167.5bcd	154.1ab	33.4ab	28.9ab
RDN + Zn **	217.9a	194.8a	528.2a	497.2a	179.9a	164.3a	35.7a	30.9a
75% RDN	164.4fg	155.4f	450.5efg	431.8defgh	141.4fg	133.7cd	28.9bcd	25.1bcd
75% RDN + Zn	167.3f	156.4ef	458.8f	437.2defg	142.2fg	134.0c	28.6cde	24.3cde
75% RDN + MC1	185.2de	163.7d	490.3cd	468.5c	160.2cde	148.7b	29.8bc	25.3bcd
75% RDN + MC1 + Zn	209.9b	188.9b	515.8ab	486.6abc	172.8abc	157.8ab	32.9abc	28.8ab
75% RDN + MC2	187.9cd	171.6c	493.4c	471.8c	164.0cd	151.1b	31.6abc	26.6bc
75% RDN + MC2 + Zn	216.1ab	194.1ab	522.9ab	491.8ab	177.8ab	163.3a	35.8a	31.6a
Nutrient management treatments	*	*	*	*	*	*	*	*
Interactions	*	*	*	*	*	*	*	*

Within a column, means followed by the same letter are not significantly different at the 0.05 level of probability by the Duncan's multiple range test. "*": Indicates significant different of treatments at the 0.05 level of probability by the Duncan's multiple range test; RDN *: Recommended dose of nutrients 120 kg N ha^{-1} and 25.8 kg P ha^{-1}; Zn **: Soil applied with 5 kg Zn ha^{-1} through zinc sulphate heptahydrate; MC1: (*Anabaena* sp. (CR1) + *Providencia* sp. (PR3) consortia; MC2: *Anabaena-Pseudomonas* biofilmed formulations.

4. Discussion

4.1. Energy Input and Type of Energy

The study of energy input is important in rice and wheat at the individual crop level as well as system level due to significant variations in cultivation practices which include CEMs, nutrient management and soil hydrological regimes across a region. The faster adoption of CEMs such as ZTW [41], which is reported to reduce the energy expenditure on tillage, promotion of consortia-based microbial inoculations for nutrient endowments in crops [42,43], thereby reducing the total nutrient applied and increasing the use of micronutrients due to crop response [44,45], was evaluated for biological parameters and economic scale, while their evaluation in terms of energy requirement carries significant importance considering their share in total energy consumption in the crop production process (Figure 1).

In our study, CEMs, rate of N and P application, Zn fertilization and microbial inoculation significantly affected the energetics of RWCS. The higher energy requirement in rice than wheat was contributed by the field preparation, nursery and higher number of irrigations [5,17]. The variation in energy inputs across CEMs in rice was governed by nursery, puddling, seed and sowing and number of irrigations, while in wheat tillage, seed rate and weeding operation contributed to the variation in energy input, with highest contribution coming from tillage. The highest share of fertilization to total energy consumption [18,46] was due to the energy equivalent for N (60.6 MJ kg^{-1}), P_2O_5 (11.1 MJ kg^{-1}) and K_2O (6.7 MJ kg^{-1}) and the higher quantity (90–120 kg N, 44.67–59.1 kg P_2O_5 and 60 kg K_2O) applied, while higher energy equivalents for tractor-operated machinery and diesel increased the share of field preparation in total energy input. As the share of fertilizer in energy consumption is higher in wheat, the increase in energy efficiency by using microbial consortia will be more profitable for wheat. The variation in energy requirement due to irrigation was contributed by rice alone as the irrigation requirement of all CEMs in wheat remained the same. The saving in energy by changing CEM from PTR to ARS was 563.7 MJ ha^{-1} (2%). At the same time, this contribution was less if calculated based on monetary terms at the farmer field level which might be due to the subsidized rate of electricity and very low irrigation charges. At the system level, the share of irrigation in total energy input remained the same (6%) even though the difference in energy consumption in irrigation among CEMs is 326.6 MJ ha^{-1}. The reduction in energy requirement by changing CEM was reported by [17,47].

The ARS and ZTW were found to be better as they use higher renewable energy than PTR and CDW. The use of higher seed rate and absence of puddling and tillage in ARS and ZTW were the important reasons for higher renewable energy consumption. At the same time, total energy input was also lower in ARS and ZTW which makes them energy-efficient. Both methods were also recommended on the issue of water shortage [48,49] and timely planting along with energy efficiency [7]. Among nutrient management treatments, the use of microbial inoculations reduces the share of non-renewable energy; therefore, treatment with 75% RDN + MC1 or MC2 increases the share of renewable energy in crop production.

The variation in gross energy production arose due to yield superiority of PTR [50] and SRI [51] over ARS in rice and ZTW [52] over CDW and SWI in wheat. The higher gross energy than ARS and lower energy input than PTR make SRI significantly superior in net energy production. The variation across CEMs in energy input and net energy production [53,54] was also reported. We found that in rice and wheat, the variations in energy input and gross energy production contribute equally towards the variation in net energy production among CEMs, while at the system level, the variation in input has the highest contribution to the increase in net energy production.

4.2. Energy Production

Among the nutrient management options, gross and net energy output was affected significantly by the rate of N and P application, Zn fertilization and microbial inoculation. The rate of N and P application had the highest contribution to variation in energy production, while Zn fertilization had the lowest contribution to energy production. The highest gross energy in RDN + Zn was the outcome of highest yield, while the highest net energy production in 75% RDN + Zn + MC1 or MC2 was due to reduction in cost of cultivation on 25% of N and P fertilizer. The difference in energy input across CEMs had a higher contribution to the variation in net energy production than gross energy production. The variation in energy input across CEM was 6.53×10^3 to 15.47×10^3 MJ ha^{-1} for rice, 3.95 to 12.19 MJ ha^{-1} for wheat and 10.49 to 27.66 MJ ha^{-1} for RWCS, while variation in gross energy production was 125.0–157.1, 125.7–153.1 and 250.9–309.2 MJ ha^{-1} for rice, wheat and RWCS, respectively.

The nutrient application through chemical fertilizers is the single most important source of nutrients. Its importance has increased over the years due to increasing nutrient deficiency [55,56], response to fertilization and use of high-yielding nutrient responsive varieties. In terms of energy, fertilizer contributes 59–64% to total energy input in RWCS and the cost of chemical fertilizer is also going to increase in future on account of the increasing cost of fertilizer production, depletion in natural reserves and increasing demand. The rice and wheat together contribute 61% (17.67 million tonnes) to total fertilizer consumption in India. Considering this, complimentary options such as use of microbial inoculations with partial replacement of chemical fertilizers will help in making the RWCS more energy-efficient.

4.3. Grain Yield, Protein Yield and Micronutrient Uptake

The calculations of nutritional status of staple crops are essential considering the shifting of focus of India from food security to nutritional security [57,58]. Protein energy malnutrition (PEM) ranks first among the major nutrition-related disorders in India [21]. As both rice and wheat are the staple crops catering the protein need of the majority of the population (especially BLP where PEM is a severe problem), the calculation of their protein yield will be more focused than just the calculation of yield. In our experiment, the variation in protein yield was accounted due to the variation in grain yield of rice and wheat and the factor used for calculation converting nitrogen content to protein. The yield variations in rice recorded due to better crop establishments leading to superior growth and yield attributes due to transplanting in both PTR and SRI and less weed menace due to puddling than ARS. The variation in yields response by different CEMs was reported by [59,60], while variation in weed dynamics across CEMs [61] and weed problem in aerobic rice [62] was also reported. This significantly higher yield variation across CEMs nullified the effect of factor used for calculation of protein yield which is higher in rice (5.95) than wheat (5.70).

Another health-related risk is micronutrient deficiency also called as hidden hunger [63]. The need and significant of micronutrient application for enhancing yield [20] as well as increasing grain micronutrient concentration and uptake was reported [64], while their uptake variation across the CEMs with use of different microbial inoculations is meagre and studied in this investigation. The uptake of all studied micronutrients was higher in wheat. Along with uptake, concentration dilution by dry matter production and presence of anti-nutritional factors (phytate) [65] are the other factors deciding the nutritional status of food grains. The higher micronutrient uptake in PTR and SRI signifies the role of puddling in enhancing the uptake of micronutrients [66], while significantly higher micronutrient uptake in ZTW is the indication of the superior performance of ZTW arose due to residual effect of previous season rice (ARS) and better root growth leading higher forage area due to less physical constraints for root growth (non-puddled ARS). The uptake of Zn and Fe in both rice and wheat was significantly affected by application of microbial inoculations, RDN and Zn fertilization. This indicates ability of above-mentioned factors in amending the micronutrient uptake in rice. The variation in micronutrient uptake across the CEMs was explained by changes in hydrological regimes across CEMs in rice and residual effect as well as soil physical constraints in wheat.

5. Conclusions

The crop establishment methods (CEMs) differ significantly in energy input and output along with protein and micronutrient uptake in both years of study. The gross and net energy production was highest in ARS–ZTW which was 293.9 $\times$ 10^3 MJ ha^{-1} and 273.5–267.6 $\times$ 10^3 MJ ha^{-1}, respectively. The protein yield increase in ARS–ZTW was 61.5–62 kg ha^{-1} in the first year and 86.2–88.3 kg ha^{-1} in the second year over other CEMs, respectively,, while it reduced the energy required for the production of one tonne of system yield by 206 and 250 MJ tonne^{-1} over PTR–CDW in the first and second year, while the same for SRI–SWI was 467 and 517 MJ tonne^{-1}, respectively, for the first and second year. The application of 75% RDN with microbial consortia and Zn showed promise in enhancing net and gross energy production over all other combinations. This signifies their role of microbial consortia in energy efficiency and nutrient security of RWCS. The future research may focus on evaluation and standardization of microbial consortia in other crops and cropping systems under diverse ecologies. Furthermore, understanding the physiological and biochemical processes or mechanisms which are affected by the microbial consortia in rice and wheat can be an innovative line of research work. Besides this, the energy inputs and output and energy efficiency need to be studied for the increased level of mechanization in crop production as the lack of labour availability and higher wage rate in the future will increase mechanization in crop production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14105986/s1. Table S1: Mean weekly meteorological data during the rice-growing season in 2013 and 2014; Table S2: Mean weekly meteorological data during the wheat growing season in 2013–14 and 2014–15.

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