Water, Nutrient, and Energy-use Efficiencies of No-till Rainfed Cropping Systems with or without Residue Retention in a Semi-Arid Dryland Area

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ABSTRACT

No-till rainfed cropping systems are being considered by farmers to make farming more profitable by reducing production costs, thereby enhancing resource-use efficiency. Field studies were conducted at the Indian Agricultural Research Institute (IARI), New Delhi during rainy and winter seasons of 2010-2011 and 2011-2012 to examine consumptive use of water (CW), water-use efficiency (WUE), nutrient uptake and balance, and energy-use efficiency (EUE) of nine diverse cropping systems based on three rainy season crops - pearl millet (*Pennisetum glaucum* (L.) R. Br.), cluster bean (*Cyamopsis tetragonoloba* L.), and green gram (*Vigna radiata* L. Wilczek) followed by three winter crops - wheat (*Triticum aestivum* L.), chickpea (*Cicer arietinum* L.), and mustard (*Brassica juncea* L.) in each of those three rainy season crop planted fields under no-till semi-arid rainfed conditions. Three residue treatments [i.e., no residue, crop residue, and Ipil-ipil {*Leucaena leucocephala* (Lam) twigs}] were examined for both rainy season and winter crops. Retention of crop residues significantly increased soil moisture, CW, and WUE in all cropping systems. Good growth of mustard, chickpea, and wheat after cluster bean, and a large amount of cluster bean green pods resulted in substantially higher CW and WUE of cluster bean-based systems compared to pearl millet- and green gram-based systems. Crop nutrient uptake increased substantially under crop residue and *Leucaena* twigs treatments compared to no-residue control plots due to enhanced crop growth and augmentation of nutrients. However, nutrient uptake and apparent nutrient balances varied greatly among cropping systems. Energy input requirement increased by approximately 10 times under crop residue and *Leucaena* twigs treatments. As a result, net energy balance and EUE were substantially higher for no-residue treatments. *Leucaena* twigs treatments had higher net energy balance and EUE than crop residue treatments, indicating the importance of leguminous residues in crop production. Results indicate the necessity of exercising optimal balance between retention of crop residues and energy inputs for the long-term soil health and sustainability of cropping systems.

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1. Introduction

Due to declining water availability for agriculture, rainfed agriculture is gaining importance worldwide as it covers about 80% of the global agricultural area and shares about 60% of the global food-grain production (Rockström et al., 2010). The future prosperity of India relies on rainfed agriculture as 67% of 143 M ha net cultivated area, 91% of coarse grains and pulses, 80% of oilseeds, 60% of cotton (*Gossypium hirsutum* L.), 50% of rice (*Oryza sativa* L.), and 19% of wheat (*Triticum aestivum* L.) grown areas are under rainfed conditions, most dominantly in the semi-arid drylands of north-western India (Gupta, Jat, Gopal & Kumar, 2010; Prasad & Bhatia, 2009).

Conventional agriculture with intensive conventional tillage (CT) systems with the use of heavy machinery can lead to a decrease in soil organic matter (SOM), loss of soil structure and fertility, and overall deterioration of soil health (Pingali, Vignozzi & Pellegrini, 2004). In comparison, conservation agriculture (CA) systems involve minimum soil disturbance, maintain soil cover through crop residues or other mulching materials, and follow dynamic crop rotations for achieving higher

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productivity and sustainability (Hobbs, 2007; Sayre & Hobbs, 2004). The CA systems have gained importance globally as they are more energy efficient and beneficial to the environment as compared to conventional systems (Filipovic, Silvio, Zlatko, Robert & Djuro, 2006; Hariram, Saimi, Kler, Timsina & Humphreys, 2012; Sharma, Chokkar, Rani, Gathis & Kumar, 2002). The CA systems, including no-till (NT) practices, save fuel energy, restrict release of soil organic carbon (SOC), and mitigate carbon dioxide concentration in the atmosphere (Grace, Jain, Harrington & Philip, 2003; Rao, Singh, Joshi & Ramakrishna, 2000; Saha et al., 2010). Thus, NT practices have a great potential to sequester carbon, increase SOM, minimize soil erosion, and reduce production costs by maintaining a similar production level (Gathala et al., 2011a, 2016; Rao et al., 2000). Research findings from several locations in the Indo-Gangetic plains of South Asia showed saving of land preparation costs by about US$25-50 ha^{-1} and reductions in diesel consumption by 50–60 liters ha^{-1} with NT compared to CT (Kumar et al., 2013a, 2013b; Sangar, Abrol & Gupta, 2005). Furthermore, wheat yields increased up to 30% by using NT with optimal level of energy input (Chaudhary, Gangwar & Pandey, 2006, Saharawat et al., 2010).

Retention of crop residues on the soil surface creates a physical barrier to the emergence of weeds, moderates soil temperature fluctuations, conserves soil moisture, adds SOM, improves nutrient-water interactions, and reduces air pollution arising due to large-scale burning of crop residues (Bhusan & Sharma, 2002; Sharma & Acharya, 2000; Sharma et al., 1995). When the residues are retained on the soil surface in combination with NT practices, the enhanced biological processes lead to improved soil quality (Reicosky, 2003). The importance of using the pruned materials of various trees and shrubs grown in non-cropped alley lands as brought-in residues or mulch since pre-historic time as in the *Vedas* and *Kuran* is reflected from several records, and these practices are still dominant in highlands and rainfed areas in India (Dhyani, Newaj & Sharma, 2009).

The CA system is now adopted globally on about 120 M ha, largely in rainfed areas (Derpsch & Friedrich, 2009). However, only about 2 M ha of wheat is cultivated with NT seed drills in India (Aryal, Sapkota, Jat & Bishnoi, 2015; Jat et al., 2014). In irrigated areas of north-western India, about 20 diversified cropping systems are practiced (Gill & Ahlawat, 2006), but few cropping systems with their inconsistent performance in terms of productivity, profitability, and energetics have been documented for rainfed areas. Of the few studies conducted with rainfed cropping systems, the cluster bean (*Cyamopsis tetragonoloba* L.)–mustard (*Brassica juncea* L.) system was more remunerative than the cluster bean–wheat system in Hisar, north-west India, while the cluster bean–wheat system had higher net returns with higher water-use efficiency (WUE, the efficiency to gain carbon per unit of water) in Gwalior, central India (Saxena, Singh & Joshi, 1997; Singh, Sharma, Deo, Siag & Verma, 1998). Likewise, net returns and the benefit-cost ratio were higher with the green gram (*Vigna radiata* L. Wilczek)–wheat system in Rajasthan, northern India (Singh, Singh & Patidar, 2008). Similarly, on-farm experiments conducted under rainfed conditions at 35 locations in five districts of Rajasthan revealed that the cluster bean–wheat sequence yielded the highest gross returns, followed by the cluster bean–mustard and pearl millet (*Pennisetum glaucum* (L.) R. Br.)–wheat crop sequences (Lal, Bhati & Nag, 2004). There are also records of remarkable increases in crop yields in the maize (*Zea mays* L.)–wheat system with scanty rainfall through the maintenance of appropriate vegetative cover in rainfed areas (Acharya, Kapur & Dixit, 1998; Sharma & Acharya 2000; Sharma, Singh, Tyagi & Mohan, 1998; Sharma et al., 2010). Incorporation of Ipil-ipil (*Leucaena leucocephala* (Lam)) twigs was effective for both rainy season and winter crops due to their high nitrogen (N) content and availability (Sharma & Behera, 2009; Sharma et al., 2010, Sharma, Singh, Dhyani & Dube, 2011), with significant residual effects on increasing the soil fertility and productivity of subsequent crops (Jones, Wendt, Bunderson & Itimu, 1996; Lehria, Bali & Singh, 2006). Despite several instances of sustainable productivity and profitability of rainfed cropping systems following the CA, its adoption under rainfed conditions has been slow (Pittelkow et al., 2014).

As water is the scarce and costly input for crop production in semi-arid rainfed areas, it is important to increase crop productivity and WUE of rainfed cropping systems. A distinct advantage of NT systems is that they generally maintain or increase soil macro pores and SOM content, thereby increasing the water-holding capacity of soil (McMaster, Palic & Dunn, 2002). The annual rainfall of 600-800 mm in most of the semi-arid rainfed areas may be adequate for crop growth, but its uneven distribution results in deficit moisture stress and low yields in dry rainfed areas. Thus, the development of more innovative region-specific CA systems could be an alternative approach for boosting the productivity and increasing the resource (i.e., water, fertilizer, energy) use efficiencies (Gathala et al., 2011a, 2013) for those areas. In addition, the complexities associated with residue management in NT systems indicate the need for more research for efficient utilization of crop residues. Therefore, this study was undertaken to quantify the influence of nine diverse NT rainfed double cropping systems (three rainy season crops - pearl millet, cluster bean, and green gram followed by three winter crops – wheat, chickpea (*Cicer arietinum* L.), and mustard under three residue treatments (i.e., no residue, crop residue, and *Leucaena* twigs) on water and nutrient uptake and balances, energy relations, and resource-use efficiencies in a semi-arid environment of north-west India.

2. Materials and Methods

2.1. Study Site, Soil, and Weather Details

Field experiments were conducted in a one-hectare field located at the Research Farm of the Indian Agricultural Research Institute (IARI), New Delhi (28.4º N, 77.1º E, 229 masl) during rainy (June-October) and winter (October-March) seasons of 2010-2011 and 2011-2012. The soil type was shallow (~15 cm) in depth with sandy-loam texture, bulk density of 1.55 Mg m^{-3}, and field capacity of 18.68% (w/w). It had 0.40% organic carbon (C), 147.2 kg ha^{-1} $KMnO_4$-oxidizable N, 17.0 kg ha^{-1} 0.5 N $NaHCO_3$-extractable phosphorus (P), 225.1 kg ha^{-1} 1.0 N NH_4OAc-exchangeable potassium (K), and 7.5 pH at the beginning of the experiment. The average annual rainfall of Delhi over a decade (2000-2010) was 739 mm, of which >80% occurred generally during the monsoon (rainy) period (July-September). There was ~44% higher rainfall in 2010-2011 (954 mm, ~29% higher than the mean for the past decade) than in 2011-2012 (662 mm, ~10% lower than the mean for the past decade). Winter season of 2010-2011 received about 85 mm well-distributed rainfall, but there was only 34 mm sparsely distributed rainfall in winter season of 2011-2012. The average winter season rainfall for the past decade was ~125 mm. Overall, the study site experienced contrasting weather conditions during the two years of the study period.

2.2. Management Practices and Treatment Details

The experimental land was laser-leveled during November 2009 and a uniformity trial was conducted by growing wheat cv. 'PBW-175' to standardize the field prior to the beginning of the experiment. Thereafter, continuous NT was practiced to sow all six tested crops under rainfed conditions during the entire study period of 2010-2011 and 2011-2012. Pearl millet, cluster bean, and green gram were grown during the 2010 rainy season under no-residue, crop residues, and *Leucaena* twigs in a randomized complete block design (RCBD) with four replications. On each rainy season crop (pearl millet, cluster bean, and green gram) planted fields, three winter crops (wheat, chickpea, and mustard) were grown in strips during the winter season of 2010-2011. The resulting experimental design to study nine diverse rainfed cropping systems based on three rainy season crops (pearl millet, cluster bean, and green gram) followed by three winter crops (wheat, chickpea, and mustard) was a strip-split plot design (Figure 1). Pearl millet, wheat, and mustard were grown with 60:40:20 kg NPK ha^{-1}, while cluster bean, green gram, and chickpea were grown with 20:40:20 kg NPK ha^{-1}. Diammonium phosphate (DAP, 18% N and 46% P) was applied in rows with Happy Seeder (Sidhu et al., 2007), while potassium chloride (KCl, 60% K), and urea (46% N) were broadcasted before sowing. Pearl millet, wheat, and mustard were top-dressed with 50% N between 30 and 60 days after seeding (DAS) coinciding with rainfall. After harvesting, residues were left in the fields under crop residue treatment, but they were removed from no-residue and *Leucaena* twigs treatments. Crop residues were applied at the rate of ~5.0 t ha-^{1} dry matter and *Leucaena*, brought from nearby locations, were applied at the rate of ~10.0 t ha^{-1} green twigs (~3.5 t ha^{-1} dry matter, 65-70% moisture) seasonally for both rainy season and winter crops.

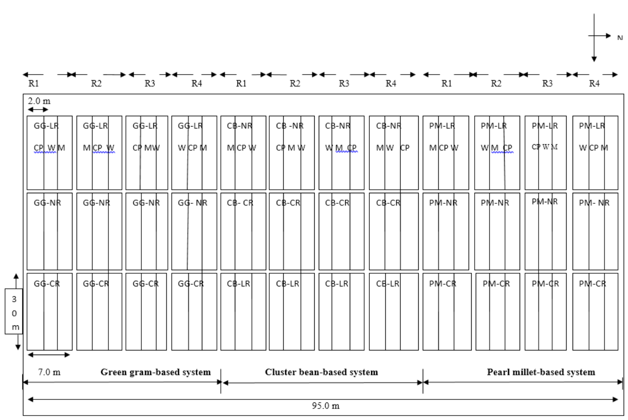

Figure 1. Layout of the experimental plot.

Note: PM = Pearl millet, NR = No residue, CR = Crop residue, LT = *Leucaena* twigs, W = Wheat, CP = Chickpea, and M = Mustard.

The seed and stover yields of rainy season crops were recorded from a 25 m^2 area in 2010 and a 10 m^2 area in subsequent seasons. Thinning was done in mustard to maintain plant-to-plant spacing of 8–10 cm. In the second year (2011–2012), mustard and chickpea sown on October 3 did not germinate due to low soil moisture coinciding with the high daily maximum temperature and evaporation throughout October. Therefore, limited irrigation (about 200,000 liters or 200 m^3 of water ha^{-1}) through 2.5 cm diameter pipe from a nearby drain was applied on the seed-rows after 30 DAS to obtain uniform plant stands. Further, the gravimetric soil profile moisture in the surface soil (0–15 cm) was only 4–5% in the plots to be sown wheat at the end of October 2011. Therefore, a pre-sowing flood irrigation equivalent to 7.0 cm was given to these fields, and wheat was sown on November 11, 2011 after attainment of optimum moisture for planting. Under irrigated conditions, the biological N_2 fixation potential of cluster bean, green gram, and chickpea have been reported to be 196, 50, and 46 kg ha^{-1} yr^{-1}, respectively (Peoples, Herridge & Ladha, 1995). In our study, only half of these values were added to determine total N inputs due to no inoculation with *Rhizobium* strains and moisture-deficient rainfed semi-arid conditions as in a previous study (Bandalucco et al., 2010).

2.3. Consumptive Water Use and Water-use Efficiency

Soil profile moisture at 0-15, 15-30, and 30-45 cm depths was measured at various growth stages of crops, from before sowing to after harvesting, using the gravimetric method. The effective rainfall was then added to the soil moisture to estimate the consumptive use of water (CW) (Allen, Pereira, Raes & Smith, 1998). Soil moisture content at different depths (volume/volume) was calculated by multiplying with respective bulk density values. Water requirement of crops was calculated based on the soil moisture depletion, effective rainfall, and irrigation amount applied to the winter crops in the second year (2011–2012). Therefore, CW was estimated for each treatment using the following equation (Michael, 2014):

$$CW = NIR + R_f + \sum \frac{n\,(Mb_i - Me_i)}{100} \times As_i \times D_i$$

where CW = seasonal consumptive use of water (mm); NIR = total irrigation water applied during the crop season (mm); R_f = seasonal rainfall (mm); Mb_i = percent moisture content at the beginning of the season of the ith layer of the soil; Me_i = percent moisture content at the end of the season of the ith layer of the soil; n = number of soil layers considered within the root zone depth (this was considered for 0-15, 15-30, and 30-45 cm); D_i = depth of the ith layer of soil within the root zone (mm); and Asi = apparent specific gravity of the ith layer of the soil.

The WUE was calculated by dividing the grain yield of an individual crop by CW of the respective crop.

2.4. Crop and System Nutrient Uptake

Plant samples of grains/seeds/green-pods as well as stalk/stover/straw of different crops collected at harvesting were dried in an oven at 60 °C for a minimum of 48 hours. The oven-dried samples were ground to pass through 40 mesh-sieve in a Macro-Wiley Mill. From each treatment, grain and by-product samples were taken for chemical analysis to determine N, P, and K concentrations. We estimated N concentration by the modified Kjeldhal method, P concentration by the Vanado-molybdo-phosphoric yellow color method, and K concentration by the Flame Photometer method following the procedure described by Prasad et al. (2006). The uptake of macro nutrients by each crop was computed by multiplying the N, P, and K concentrations with the dry weight of the respective plant parts (grain plus by-product) of each crop at harvest.

The system uptake of N, P, and K was estimated by adding nutrient uptake by the component crops for each of the three rainy season cropping systems. A nutrient balance sheet was prepared based on inputs, outputs, and net change in nutrient status before and after the study periods. Apparent nutrient balance was determined based on the total nutrient inputs (initial soil nutrients + nutrients added through recommended nutrients, crop residues, *Leucaena* twigs, and estimated biological N_2 fixation by different legumes) and nutrient outputs (available soil nutrients after harvesting + nutrient uptake both by economic and by-product yields) of all crops and cropping systems. Nutrient balance was estimated by considering the total amount of nutrients added to the soil as different nutrient management options and the total amount of nutrient uptake by grain and straw yields in each year after harvesting the respective crop. This calculation was valid particularly for N, P, and K. The annual nutrient balance (kg ha^{-1} y^{-1}) was calculated using the following equation (BARC, 2012):

$$X_a = (X_a + X_b + X_{cri}) - X_{rem}$$

where X_a = gain or loss of nutrient (kg ha^{-1}); X_f = nutrient added through inorganic sources (kg ha^{-1}); X_b = nutrient added through biological nitrogen fixation (BNF, kg ha^{-1}); X_{cri} = nutrient added by incorporation of crop residue (kg ha^{-1}); and X_{rem} = nutrient removed by cropping system (kg ha^{-1}). In addition, we also considered initial soil nutrients before planting and available soil nutrients after harvesting in the nutrient balance.

2.5. Energy Analysis

Total and net energy inputs from various input sources and outputs from grain and by-products were calculated using the published energy conversion coefficients, and expressed as input energy, output energy, and energy-use efficiency (EUE) (Devasenapathy, SenthilKumar & Shanmugam, 2009). An inventory of all inputs (e.g., fertilizers, seeds, pesticides, fuel, and human labor) to and outputs (e.g., grain and straw/stover) from all cropping systems was prepared, from which the energy values for each crop management treatment were calculated. Crop inputs and outputs were converted to energy-unit equivalents using conversion coefficients from the published literature to facilitate comparisons among treatments (Tables S1 and S2). The labor and fuel required for each farm operation (e.g., tillage, fertilizer and pesticide applications, hand-weeding, harvesting, and threshing) were recorded for each field trial. Energy outputs were calculated for both economic yield (e.g., sellable harvested product) and straw/stover yield which is used as animal feed on farms. The total energy use (TEU; total energy required to produce a crop), energy output (EO; energy produced in grain and straw products), and EUE were calculated using the following equations (Gathala et al., 2016):

$$TEU = \left[E_m + E_f + E_i\right]$$

where TEU = total energy use (MJ ha^{-1}); E_m = manual energy use from labor (in person-hours); E_f = the energy used for fuel; and E_i = the energy derived from all inputs (i.e., seed, fertilizer, agro-chemicals, and crop residues). The energy-equivalent factors used in this study are shown in Tables S1 and S2.

$$EO = [(Grain\ x\ Energy) + (Straw\ \ x\ Energy)]$$

where EO = energy output (MJ ha^{-1}); grain = crop grain yield (kg ha^{-1}); energy = specific conversion factor for grain or straw (MJ kg^{-1}); and straw = crop straw or stover yield (kg ha^{-1}).

$$EUE = \frac{EO}{TEU}$$

where EUE = energy-use efficiency (a dimensionless term); EO = energy output (MJ ha^{-1}); and TEU = total energy use (MJ ha^{-1}).

The energy inputs included both renewable (e.g., labor, seed, and crop residues) and non-renewable (e.g., chemical fertilizers, tractor, diesel, machinery, and agro-chemicals) sources of energy.

2.6. Statistical Analysis

The data on system comparisons were analyzed using the analysis of variance (ANOVA) with RCBD for 2010 rainy season crops [only three crops (pearl millet, cluster bean, and green gram) under three crop residue retention treatments (no residue, crop residues and *Leucaena* twigs)]. For the succeeding season's crops that followed the main season crop, the experimental design to analyze ANOVA was strip-split plot design. Thus, cropping systems productivity, EUE, and most of the statistical results were analyzed for the strip-split plot design. The statistical analysis was performed using the MSTAT-C software (Gomez and Gomez, 1984). Least significant difference (LSD) was calculated and treatment means were separated at 5% level of significance (P=0.05).

3. Results and Discussion

3.1. Effect of Residue Management on Consumptive Water Use and Water-use Efficiency

Crop residue management significantly increased both CW and WUE for all cropping systems in both years (Table 1). In most cases, CW was higher under crop residues than under *Leucaena* twigs treatment, but the result was inconsistent for WUE between crop residues and *Leucaena* twigs treatments. Retention of crop residues in pearl millet-based and green gram–based systems, and incorporation of *Leucaena* twigs in the cluster bean–based system resulted in higher CW and WUE, while no-retention of residues resulted in lower CW and WUE in all cropping systems. The good growth of mustard, chickpea, and wheat after cluster bean, and large amount of cluster bean green-pods resulted in substantially higher CW and WUE in cluster bean-based cropping systems as compared to pearl millet- and green gram-based cropping systems. The CW was higher in the cluster bean–based system than the other two systems due to its longer crop duration as well, which received more rainfall and had access to soil moisture at deeper depths due to deeper root systems. Increased SOC and improved soil physicochemical and microbiological properties due to the addition of a large amount of crop residues helped increase the retention of more soil moisture (data not shown). Similar to our findings, other studies also reported an improvement in soil structure, water retention capacity, infiltration rate, and hydraulic conductivity, and a decrease in bulk density with the retention or incorporation of crop residues (Edmeades, 2003; Jat et al., 2014). The presence of higher amounts of organic components in leguminous crops, and the applications of both crop residue and *Leucaena* twigs substantially increased water retention. Large numbers of storage pores in NT residue-applied plots may have resulted in higher soil moisture content at all depths (Azooz, Arshad & Franzluebbers, 1996). The enhanced soil moisture in the residue-retained NT plots can be attributed to reduced runoff and evaporation as well as greater infiltration (Pingali, Vignozzi & Pellegrini, 2004; Verhulst, Deckers & Govaerts, 2009). As a result, CW was substantially higher in residue-applied plots. Similar results were reported by several studies (Chaudhari, 1999; Gathala et al., 2011b, 2016; Saharawat et al., 2010; Singh & Singh, 1995) that increased root activity and proliferation of root system due to translocation of more photosynthates to roots that resulted in more extraction of soil moisture from deeper layers (>15 cm).

Table 1. Effect of crop residues and *Leucaena* twigs on consumptive water use (CW, mm) and water-use efficiency (WUE, kg ha^{-1} mm^{-1}) of pearl millet-, cluster bean-, and green gram-based cropping systems.

Treatment	**Rainy season crops-based system**											
	Pearl millet-based system				**Cluster bean-based system**				**Green gram-based system**			
	2010-2011		**2011-2012**		**2010-2011**		**2011-2012**		**2010-2011**		**2011-2012**	
	CW	**WUE**	**CW**	**WUE**	**CW**	**WUE**	**CW**	**WUE**	**CW**	**WUE**	**CW**	**WUE**
After wheat												
No residue	427.7	4.56	431.5	5.19	458.4	18.0	478.4	12.9	427.8	3.95	426.4	5.05
Crop residues	433.9	6.66	439.9	9.21	462.5	20.5	486.7	20.3	435.4	5.17	434.5	9.01
Leucaena twigs	429.5	7.80	434.0	8.11	463.5	24.0	479.9	22.5	430.8	4.43	427.0	7.37
Mean	430.4	6.34	435.1	7.50	461.5	20.8	481.7	18.6	431.3	4.52	429.3	7.15
After chickpea												
No residue	427.5	5.45	374.5	5.42	458.0	17.4	419.6	14.7	427.6	2.99	368.7	3.06
Crop residues	433.4	6.65	381.5	8.94	462.2	20.0	427.0	18.5	435.1	3.86	385.0	5.27
Leucaena twigs	429.5	8.66	380.6	6.75	463.1	24.3	425.8	19.0	431.2	4.59	377.6	4.55
Mean	430.1	6.92	378.9	7.04	461.1	20.6	424.1	17.4	431.3	3.82	377.1	4.30
After mustard												
No residue	427.6	6.50	375.5	5.51	458.1	18.3	420.7	12.6	427.6	5.47	373.8	3.46
Crop residues	433.4	8.17	385.2	7.33	462.5	22.4	427.4	15.8	434.8	7.24	384.4	5.39
Leucaena twigs	429.7	10.45	380.1	6.15	463.2	26.8	427.4	17.9	431.0	6.33	379.7	4.57
Mean	430.2	8.37	380.2	6.33	461.2	22.5	425.2	15.4	431.1	6.35	379.3	4.47
Overall mean	430.2	7.21	398.1	6.96	461.3	21.3	443.7	17.1	431.2	4.89	395.2	5.31
	CW						WUE					
	A	B	C	A x B	A x C	B x C	A	B	C	A x B	A x C	B x C
LSD (P=0.05)	1.78	1.44	0.91	3.4	0.58	0.58	0.50	1.18	0.89	2.45	1.73	1.73

A = Rainy season crops-based system, B = Residue management practices, C = Winter crops-based system, and LSD = Least significant difference. The CW values for year 2010-2011 remained unchanged for different winter crops because of the initial trial first started from rainy season crops in 2010.

Table 2. Nutrient concentrations and additions through crop residues and *Leucaena* twigs (mean values for 2010-2011 and 2011-2012).

Crop residues	**Applied season**	**Nutrient concentration (%)**			**Nutrient added (kg ha^{-1})**		
		N	**P**	**K**	**N**	**P**	**K**
Maize	Winter, 2009–2010	0.45	0.103	1.42	22.5	5.2	71.0
Pearl millet	Winter	0.39	0.116	1.72	19.5	5.8	86.0
Cluster bean	Winter	1.28	0.135	1.06	64.0	6.8	53.0
Green gram	Winter	1.16	0.133	1.09	58.0	6.7	54.5
Wheat	Rainy	0.45	0.103	1.48	22.5	5.2	74.0
Chickpea	Rainy	1.23	0.141	1.05	61.5	7.1	52.5
Mustard	Rainy	0.42	0.11	1.18	21.0	5.5	59.0
Leucaena twigs	Rainy and winter	2.5	0.21	1.19	87.5	7.4	41.7

Crop residues were applied at 5.0 t ha-1 dry matter and Leucaena twigs were applied at 10.0 t ha-1 green twigs (~3.5 t ha-1 dry matter).

Table 3. System uptake of nitrogen (N, kg ha^{-1}) as influenced by residue management.

Treatment	2010-2011						2011-2012					
	Pearl millet		Cluster bean	Green gram		Mean	Pearl millet		Cluster bean		Green gram	Mean
After wheat												
No residue	83.4		136.4	84.8		101.5	73.2		103.1		88.7	88.3
Crop residue	113.2		171.0	128.6		137.6	139.1		170.0		138.3	149.1
Leucaena twigs	113.2		185.5	104.5		134.4	128.1		175.9		121.3	141.8
Mean	103.2		164.3	106.0			113.5		149.7		116.1	
After chickpea												
No residue	121.4		145.3	90.0		118.9	100.6		130.0		87.2	105.9
Crop residue	145.5		187.7	128.0		153.7	163.5		177.2		146.5	162.4
Leucaena twigs	158.3		217.0	130.9		168.7	124.2		210.0		135.6	156.6
Mean	141.7		183.3	116.3			129.4		172.4		123.1	
After mustard												
No residue	108.1		148.2	108.3		121.5	87.8		129.8		76.3	98.0
Crop residue	144.3		209.5	160.9		171.6	145.8		170.7		120.5	145.7
Leucaena twigs	158.0		239.2	140.6		179.3	114.9		183.3		112.6	137.0
Mean	136.8		199.0	136.6			116.2		161.3		103.1	
Overall mean	127.3		182.2	119.6			119.7		161.1		114.1	
	A	B	C	A x B	A x C	B x C	A	B	C	A x B	A x C	B x C
LSD (P=0.05)	7.78	8.44	0.91	13.4	1.58	1.58	5.5	6.2	3.9	8.45	6.73	6.73

A = Rainy season crops-based system, B = Residue management practices, C = Winter crops-based system, and LSD = Least significant difference.

Table 4. System uptake of phosphorus (P, kg ha^{-1}) as influenced by residue management.

Treatment	2010-2011						2011-2012					
	Pearl millet		Cluster bean		Green gram	Mean	Pearl millet		Cluster bean		Green gram	Mean
After wheat												
No residue	21.9		18.4		13.1	17.8	20.1		14.7		15.4	16.7
Crop residue	29.2		24.2		20.0	24.5	35.1		26.4		25.2	28.9
Leucaena twigs	29.2		26.1		16.2	23.8	34.3		28.6		20.8	27.9
Mean	26.7		22.9		16.4		29.8		23.2		20.4	
After chickpea												
No residue	23.5		16.9		9.8	16.7	22.1		14.5		9.3	15.3
Crop residue	28.2		20.9		13.7	21.0	30.9		18.5		15.2	21.5
Leucaena twigs	29.2		24.5		13.3	22.3	25.7		22.4		14.3	20.8
Mean	27.0		20.8		12.2		26.3		18.4		12.9	
After mustard												
No residue	26.7		21.7		17.2	21.9	25.4		18.3		11.8	18.5
Crop residue	36.3		32.2		26.5	31.7	41.2		26.2		21.8	29.8
Leucaena twigs	38.0		36.7		23.6	32.8	33.8		27.3		19.0	26.7
Mean	33.7		30.2		22.4		33.5		24.0		17.5	
Overall mean	29.1		24.6		17.0		29.9		21.9		17.0	
	A	B	C	A x B	A x C	B x C	A	B	C	A x B	A x C	B x C
LSD (P=0.05)	1.2	1.07	0.34	1.8	0.58	0.58	1.63	1.41	1.12	2.09	1.95	1.95

A = Rainy season crops-based system, B= Residue management practices, C = Winter crops-based system, and LSD = Least significant difference.

Table 5. System uptake of potassium (K, kg ha^{-1}) as influenced by residue management.

Treatment	2010-2011				2011-2012			
	Pearl millet	Cluster bean	Green gram	Mean	Pearl millet	Cluster bean	Green gram	Mean
After wheat								
No residue	130.8	93.0	91.9	105.2	96.9	67.7	82.0	82.2
Crop residue	188.5	135.0	154.6	159.4	191.0	118.4	133.2	147.5
Leucaena twigs	168.8	133.8	113.5	138.7	178.3	122.7	110.9	137.3
Mean	162.7	120.6	120.0		155.4	102.9	108.7	
After chickpea								
No residue	139.6	85.6	67.3	97.5	119.8	77.2	64.0	87.0
Crop residue	174.8	104.6	91.3	123.6	182.1	104.0	102.6	129.6
Leucaena twigs	161.4	117.3	83.1	120.6	145.9	130.4	99.5	125.3
Mean	158.6	102.5	80.6		149.3	103.9	88.7	
After mustard								
No residue	134.9	99.3	89.5	107.9	124.3	95.9	63.7	94.6
Crop residue	202.6	153.2	143.0	166.3	222.1	142.9	122.4	162.5
Leucaena twigs	191.5	173.1	126.0	163.5	177.1	142.8	107.7	142.6
Mean	176.3	141.9	119.5		174.5	127.2	98.0	
Overall mean	165.9	121.7	106.7		159.7	111.3	98.4	

	2010-2011 A	B	C	A x B	A x C	B x C	2011-2012 A	B	C	A x B	A x C	B x C
LSD (P=0.05)	10.3	7.21	2.47	7.21	4.28	4.28	10.0	7.41	6.14	9.68	10.6	10.6

A = Rainy season crops-based system, B = Residue management practices, C = Winter crops-based system, and LSD = Least significant difference.

Table 6. Total input energy (MJ ha^{-1}) expended for cultivation of rainy season and winter season crops under no till with residues management (mean values for 2010-2011 and 2011-2012).

Particulars	Common energy	Variable energy	Total energy	Particulars	Common energy	Variable energy	Total energy
A. Rainy season crops				B. Winter season crops			
1. Pearl millet				1. Wheat			
No residues	5812	0	5812	No residues	7534	0	7534
Crop residues	5812	62547	68359	Crop residues	7534	62547	70081
Leucaena twigs	5812	43906	49719	Leucaena twigs	7534	43906	51440
2. Cluster bean				2. Chickpea			
No residues	3791	0	3791	No residues	4447	0	4447
Crop residues	3791	62547	66368	Crop residues	4447	62547	66994
Leucaena twigs	3791	43906	47698	Leucaena twigs	4447	43907	48353
3. Green gram				3. Mustard			
No residues	3907	0	3907	No residues	5857	0	5857
Crop residues	3907	62547	66454	Crop residues	5857	62547	68404
Leucaena twigs	3907	43907	47813	Leucaena twigs	5857	43907	49764

Table 7. Gross input and output energy ($x10^3$ MJ ha^{-1}), energy-use efficiency, and net energy balance of pearl millet–based systems as affected by residue management.

Treatment	2010-2011				2011-2012			
	Energy output	Energy input	Energy-use efficiency	Net energy balance	Energy output	Energy input	Energy-use efficiency	Net energy balance
After wheat								
No residue	171.8	13.3	12.9	158.5	133.2	13.3	10.0	119.9
Crop residues	240.1	138.4	1.7	101.6	254.6	138.4	1.8	116.2
Leucaena twigs	224.3	101.2	2.2	123.1	236.4	101.2	2.3	135.3
Mean	212.1	84.3	5.6	127.7	208.1	84.3	4.7	123.8
After chickpea								
No residue	185.2	10.3	18.0	174.9	159.1	10.3	15.5	148.8
Crop residues	228.6	135.4	1.7	93.2	237.3	135.4	1.8	102.0
Leucaena twigs	222.6	98.1	2.3	124.6	192.8	98.1	2.0	94.8
Mean	212.1	81.2	7.3	130.9	196.4	81.2	6.4	115.2
After mustard								
No residue	198.4	11.7	17.0	186.7	161.6	11.7	13.9	150.0
Crop residues	283.4	136.8	2.1	146.6	283.0	136.8	2.1	146.2
Leucaena twigs	282.8	99.5	2.8	183.3	226.1	99.5	2.3	126.6
Mean	254.8	82.6	7.3	172.2	223.6	82.6	6.1	140.9
Overall mean	226.4	82.7	6.7	143.6	209.4	83.7	5.7	126.6

	Energy output						Energy use efficiency					
	A	B	C	A x B	A x C	B x C	A	B	C	A x B	A x C	B x C
LSD (P=0.05)	7.8	0.79	1.07	7.4	1.11	1.11	0.58	0.41	0.69	1.15	0..44	0.44

A = Rainy season crops-based system, B = Residue management practices, C = Winter crops-based system, and LSD = Least significant difference.

Table 8. Gross input and output energy ($x10^3$ MJ ha^{-1}), energy-use efficiency, and net energy balance of cluster bean–based systems as affected by residue management.

Treatment	2010-2011				2011-2012			
	Energy output	Energy input	Energy use efficiency	Net energy balance	Energy output	Energy input	Energy use efficiency	Net energy balance
After wheat								
No residue	127.6	11.3	11.3	116.3	92.2	11.3	8.1	80.9
Crop residues	179.1	136.4	1.3	42.7	166.9	136.4	1.2	30.4
Leucaena twigs	180.8	99.1	1.8	81.7	173.9	99.1	1.8	74.7
Mean	162.5	82.3	4.8	80.2	144.3	82.3	3.7	62.0
After chickpea								
No residue	118.6	8.2	14.4	110.4	107.8	8.2	13.1	99.5
Crop residues	148.9	133.3	1.1	15.6	146.1	133.3	1.1	12.8
Leucaena twigs	167.3	96.1	1.7	71.2	178.2	96.1	1.9	82.1
Mean	144.9	79.2	5.8	65.7	144.0	79.2	5.3	64.8
After mustard								
No residue	144.3	9.6	15.0	134.6	130.8	9.6	13.6	121.1
Crop residues	229.4	134.7	1.7	94.6	189.3	134.7	1.4	54.6
Leucaena twigs	258.4	97.5	2.7	160.9	200.7	97.5	2.1	103.2
Mean	210.7	80.6	6.4	130.1	173.6	80.6	5.7	93.0
Overall mean	172.7	80.7	5.7	92.0	154.0	80.7	4.9	73.3

	Energy output						Energy use efficiency					
	A	B	C	A x B	A x C	B x C	A	B	C	A x B	A x C	B x C
LSD (P=0.05)	2.3	0.37	0.41	1.78	0.76	0.76	0.28	0.22	0.35	0.73	0..23	0.23

A = Rainy season crops-based system, B = Residue management practices, C = Winter crops-based system, and LSD = Least significant difference.

Table 9. Gross input and output energy (x10^3 MJ ha^{-1}), energy-use efficiency, and net energy balance of green gram–based systems as affected by residue management.

`Treatment	2010-2011				2011-2012			
	Energy output	Energy input	Energy- use efficiency	Net energy balance	Energy output	Energy input	Energy- use efficiency	Net energy balance
After wheat								
No residue	113.6	11.4	9.9	102.1	109.5	11.4	9.6	98.1
Crop residues	189.7	136.5	1.4	53.2	181.4	136.5	1.3	44.9
Leucaena twigs	142.4	99.3	1.4	43.2	150.1	99.3	1.5	50.9
Mean	148.6	82.4	4.3	66.2	147.0	82.4	4.1	64.6
After chickpea								
No residue	86.8	8.4	10.4	78.4	88.5	8.4	10.6	80.1
Crop residues	123.8	133.4	0.9	-9.6	139.2	133.4	1.0	5.8
Leucaena twigs	114.8	96.2	1.2	18.6	134.3	96.2	1.4	38.1
Mean	108.5	79.3	4.2	29.1	120.7	79.3	4.3	41.3
After mustard								
No residue	133.3	9.8	13.7	123.5	88.8	9.8	9.1	79.0
Crop residues	212.1	134.9	1.6	77.2	165.5	134.9	1.2	30.7
Leucaena twigs	184.4	97.6	1.9	86.8	144.2	97.6	1.5	46.7
Mean	176.6	80.7	5.7	95.8	132.8	80.7	3.9	52.1
Overall mean	144.5	80.8	4.7	63.7	133.5	80.8	4.1	52.7

	Energy output						Energy use efficiency					
	A	B	C	A x B	A x C	B x C	A	B	C	A x B	A x C	B x C
LSD (P=0.05)	1.4	0.29	0.32	1.17	0.43	0.43	0.19	0..14	0.29	0.51	0..17	0.17

A = Rainy season crops-based system, B = Residue management practices, C = Winter crops-based system, and LSD = Least significant difference.

Due to several advantages associated with the application of crop residues, it can improve crop yields (Jin & Yibing, 2001). Significantly higher pearl millet-equivalent yield was obtained for cluster bean after wheat and chickpea under *Leucaena* twigs, followed by residue retention than other rainy season crops (pearl millet and green gram). Significantly higher wheat-equivalent yields (4.15 t ha^{-1} in 2010-2011 and 3.77 t ha^{-1} in 2011-2012) were obtained for mustard under *Leucaena* twigs after cluster bean. Although both yield and CW increased under residue treatments, more increase in yield than the corresponding increase in CW by applying residues resulted in higher WUE. These results were consistent with the results from previous studies (Gathala et al., 2013; Wanga et al., 2010). Another study also reported that incorporation of crop residues increased WUE by 10-20% in arid and semi-arid regions of China (Deng, Shan, Zhang & Turner, 2006).

3.2. Effect of Residue Management on System Level Nutrient Uptake and Balances

The N, P, and K concentrations and nutrient additions through crop residues and *Leucaena* twigs had substantial variations among crops due to differences in nutritional contents of the residues (Table 2). System uptake of N (Table 3), P (Table 4), and K (Table 5), and apparent nutrient balances (Figures 2, 3, and 4) revealed that the residue retention of the preceding crops resulted in significant variations in uptake and balances of N, P, and K for the cropping systems. The actual balances of different nutrients varied widely across treatments because of the addition of recommended doses of fertilizers along with the crop residues, *Leucaena* twigs, and variable quantities of biomass through leaf litter, root, and nodule biomass of legumes, as well as root and stubbles of wheat, pearl millet, and mustard.

There were smaller uptakes of N, P, and K for all cropping systems under no-residue control plots (Tables 3, 4, and 5). No-residue plots received only the blanket dose of recommended N, P, and K, and hence the system uptake was less because of reduced biomass production and less availability of nutrients. Uptake of N, P, and K increased substantially under crop residue and *Leucaena* twigs treatments due to enhanced aboveground plant growth and root growth, and addition of nutrients. In general, as compared to crop residue treatment, uptake of N, P, and K increased for the cluster bean-based system and decreased for the green gram-based system under the *Leucaena* twigs treatment (Tables 3, 4, and 5). However, for the pearl millet-based system, N and P uptakes were higher in 2010-2011 but lower in 2011-2012 under *Leucaena* twigs treatment as compared to crop residue treatment. Uptake of K was higher under crop residue than *Leucaena* twigs treatment for the pearl millet-based system in both years (Table 5).

Crop residue application added more K to the systems, while *Leucaena* twigs added more N and P (Table 2). The good growth of mustard, chickpea, and wheat after cluster bean, and large amounts of cluster bean green-pods resulted in substantially higher uptake of N in cluster bean-based systems as compared to pearl millet- and green gram-based systems. Pearl millet-based systems had higher uptake of P and K than the other two systems because of the higher biomass produced by the pearl millet-based system in comparison to cluster bean and green gram-based systems. Consistent with our findings, previous studies have also documented higher nutrient uptake with crop residue incorporation in pearl millet (Das & Gautam, 2003; Sarker, Patra, Mula & Paramanik, 2011; Vyas, Patel, Patel & Khanpara, 1994; Yadav, Kumar & Kumar, 2009), cluster bean (Buttar, Thind, Saroa & Grover, 2009; Solanki & Sahu, 2007), and green gram-based systems (Singh et al., 2008). The similar findings have been recorded for the rice-maize rotations in South Asia (Kumar et al., 2013a; Singh, Singh & Timsina, 2005, Timsina, Jat & Majumdar, 2010).

The apparent N, P, and K balances for various cropping systems were mostly positive for N and P, and negative for K at the end of two years of the experiment, more likely due to low initial status of K fertility and more uptake of K by the cereal-based systems (Figures 2, 3, and 4). Legumes like chickpea, cluster bean, and green gram fix atmospheric N_2 and help increase the input of N under legume-based systems. In addition, we had applied the recommended dose of 20 kg N ha^{-1} to legumes and 60 kg N ha^{-1} to nonlegumes (pearl millet, wheat, and mustard) as suggested by Reddy & Reddi (2009).

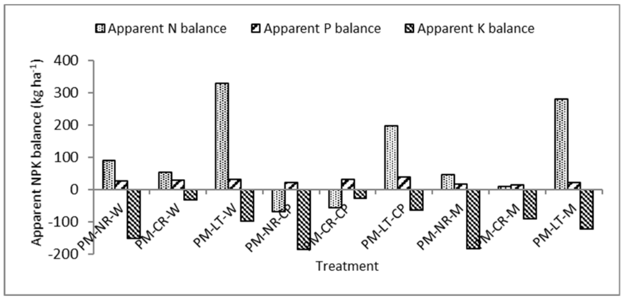

Figure 2. Apparent balance of nitrogen (N), phosphorus (P), and potassium (K) in pearl millet–based systems as influenced by residue management after two years of experiment.

Note: PM = Pearl millet, NR = No residue, CR = Crop residue, LT = *Leucaena* twigs, W = Wheat, CP = Chickpea, and M = Mustard.

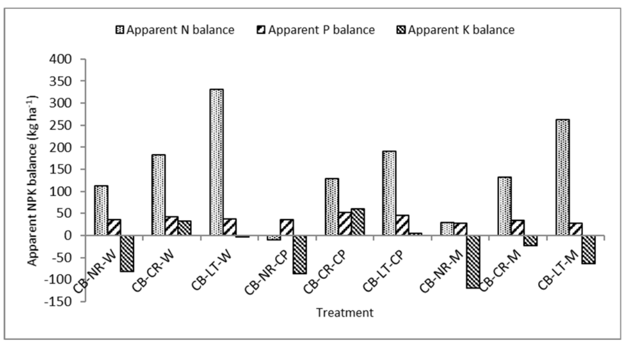

Figure 3. Apparent balance of nitrogen (N), phosphorus (P), and potassium (K) in cluster bean -based systems as influenced by residue management after two years of experiment.

Note: CB = Cluster bean, NR = No residue, CR = Crop residue, LT = *Leucaena* twigs, W = Wheat, CP = Chickpea, and M = Mustard.

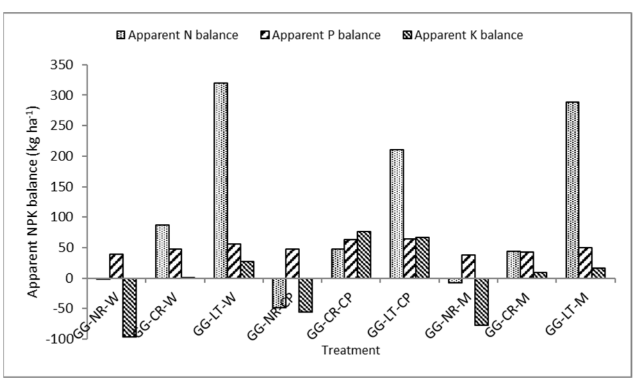

Figure 4. Apparent balance of nitrogen (N), phosphorus (P), and potassium (K) in green gram–based systems as influenced by residue management after two years of experiment.

Note: GG = Green gram, NR = No residue, CR = Crop residue, LT = *Leucaena* twigs, W = Wheat, CP = Chickpea, and M = Mustard.

3.3. Effect of Residue Management on Crop Energetics

Input energy consumptions (both renewable and non-renewable) varied across various residue management practices (Table 6). Residue management increased input energy due to the addition of 5 t ha^{-1} dry biomass of crop residues and 3.5 t ha^{-1} dry biomass of *Leucaena* twigs in all cropping systems (Tables 7, 8, and 9). The common energy sources were fertilizer, seed, labors, and agro-chemicals. Higher variable energy was required to incorporate 5 t ha^{-1} dry matter of crop residue (~62,500 MJ ha^{-1}) than to incorporate 3.5 t ha^{-1} dry matter of *Leucaena* twigs (~44,000 MJ ha^{-1}). Chaudhary et al. (2006) reported that the high energy value of crop residue (12.5 MJ kg^{-1}) was the reason for the maximum energy requirement by the residue retention treatments. Input energy was higher for crop residue treatment than *Leucaena* twigs treatment. The input energy requirement under crop residue and *Leucaena* twigs was about 11 and 9 times higher, respectively, than under no-residue for all cropping systems. The results highlighted the importance of applying leguminous residues in crop production to reduce energy usage.

Gross output energy produced by the pearl millet–based system was higher than cluster bean– and green gram–based systems due to higher biomass of pearl millet than cluster bean and green gram. In 2010, the highest gross output energy was produced under pearl millet after mustard (283.4 x 10^3 MJ ha^{-1}) followed by pearl millet after wheat (240.1 x 10^3 MJ ha^{-1}), both under crop residue retention. The highest gross output energy under the pearl millet–based system after mustard with residue retention was due to the comparatively higher biomass yield of pearl millet and mustard. Consistent with our findings, Mandal et al. (2002) also reported a higher energy requirement of the pearl millet–based system due to high energy consumed by crop residues and fertilizers. The lowest gross output energy under no residue retention under all three cropping systems was due to their lower yield performance. The treatment with no residue recorded the lowest energy requirement of all cropping systems due to savings of energy that would otherwise be needed with residue retention.

Maximum net energy was recorded under the pearl millet–based system with no residue after mustard (186.7 x 10^3 MJ ha^{-1}) followed by chickpea (174.9 x 10^3 MJ ha^{-1}) and wheat (158.5 x 10^3 MJ ha^{-1}) during 2010-2011, while the lowest net energy production was observed under crop residue retention. Maximum EUE was recorded for no-residue treatment after chickpea and mustard (17–18) under the pearl millet–based system in 2010-2011 than in the other two systems. The EUE was substantially lower under crop residue and *Leucaena* twigs treatments as compared to no-residue treatment for all cropping systems due to higher energy requirements. Thus, even though yield performance was better under crop residue and *Leucaena* twigs treatments, they did not improve EUE.

4. Conclusion

The study determined the influence of nine cropping systems with conservation agricultural practices on the water and nutrient uptake and balance, energy relations, and resource-use efficiencies under a no-till semi-arid environment of India. The CW and WUE were higher for cluster bean–chickpea and cluster bean–mustard systems under *Leucaena* twigs and crop residue retention cropping systems. Both CW and WUE were substantially higher for all cropping systems under crop residue and *Leucaena* twigs treatments as compared to no-residue treatment. Uptakes of nutrients (N, P, and K) were smaller for all cropping systems under no-residue treatment, most likely due to reduced productivity and less availability of nutrients. Input energy, gross output energy, net output energy, and EUE were relatively higher under the pearl millet–based system than cluster bean– and green gram–based systems due to the higher biomass of pearl millet. As residue management increased the input energy, no-residue treatment showed higher EUE. The results indicated that the retention of crop residues might require more energy input in rainfed cropping systems. Thus, an optimal balance between retention of crop residues and energy inputs might be critical for the long-term sustainability of rainfed cropping systems.

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Table S1. Economics and input/output energy (MJ ha^{-1}) for different crops and cropping systems (mean values for 2010-2011 and 2011-2012).

No.	Particulars	Pearl millet		Cluster bean		Green gram		**Energy coefficients
	A. Inputs (fixed cost)	Unit expenditure	Energy (MJ)	Unit expenditure	Energy (MJ)	Unit expenditure	Energy (MJ)	
1	Seed	4 kg	58.8	30 kg	441.0	40 kg	588.0	14.7 MJ/kg
2	Sowing (Happy-seeder)	3 hrs/ha	675.7	3 hrs/ha	675.7	3 hrs/ha	675.7	4 l/hr (56.3 MJ/l)
3	Fertilizer							
	i. N	60 kg	3636.0	20 kg	1212.0	20 kg	1212.0	60.6 MJ/kg
	ii. P	40 kg	444.0	40 kg	444.0	40 kg	444.0	11.1 MJ/kg
	iii. K	20 kg	134.0	20 kg	134.0	20 kg	134.0	6.7 MJ/kg
4	Herbicides and application							
	I. Pre-sowing	0.75 l	135.0	0.75 l	135.0	0.75 l	135.0	120 MJ/kg
	ii. After sowing	1.5 l	180.0	1.5 l	180.0	1.5 l	180.0	120 MJ/kg SC*
	iii. Application	2 laborers	31.4	2 laborers	31.4	2 laborers	31.4	1.96 MJ/man- hr
5	Gap filling and thinning	3 laborers	47.0	2 laborers	31.4	2 laborers	31.4	1.96 MJ/man- hr
6	Hand weeding	0	0.0	5 laborers	78.4	0	0.0	1.96 MJ/man- hr
7	i. Insecticide	0	0.0	2 l	240.0	2 l	240.0	120 MJ/kg SC*
	iii. Application	0	0.0	2 laborers	31.4	2 laborers	31.4	1.96 MJ/man- hr
8	Bird watching (15 days)	15 laborers	235.2	0	0.0	0	0.0	1.96 MJ/man- hr
9	Harvesting	10 laborers	156.8	10 laborers	156.8	10 laborers	156.8	1.96 MJ/man- hr
10	Threshing	5 laborers	78.4	0	0.0	3 laborers	47.0	1.96 MJ/man- hr
	Total		5812.3		3791.0		3906.6	
	B. Inputs (Variable cost)							
1	Crop residues							
	i. Amount	5.0 t /ha dry mass	62500.0	5.0 t /ha dry mass	62500.0	5.0 t /ha dry mass	62500.0	12.5 MJ/kg
	ii. Application cost	3 laborers	47.0	3 laborers	47.0	3 laborers	47.0	1.96 MJ/man- hr
	Total		62547.0		62547.0		62547.0	
2	Leucaena twigs							
	i. Amount	3.5 t/ha dry mass	43750.0	3.5 t/ha dry mass	43750.0	3.5 t/ha dry mass	43750.0	12.5 MJ/kg
	ii. Application cost	10 laborers	156.8	10 laborers	156.8	10 laborers	156.8	1.96 MJ/man- hr
	Total		43906.8		43906.8		43906.8	
	C. Output							
1	Main product							14.7 MJ/kg
2	By-product							MJ/kg

SC* = Super chemicals; *8 hours/day **Energy co-efficient - Source: Devasenapathy et al. (2009)

Table S2. Economics and input/output energy (MJ ha^{-1}) of winter season crops (mean values for 2010-2011 and 2011-2012).

Particulars		**Wheat**		**Chickpea**		**Mustard**		**Energy coefficients**
A. Inputs (fixed cost)		**Unit expenditure**	**Energy (MJ)**	**Unit expenditure**	**Energy (MJ)**	**Unit expenditure**	**Energy (MJ)**	
1	Seed	120 kg	1764.0	80 kg	1176.0	4 kg	100.0	14.7 MJ/kg
2	Sowing (Happy-seeder)	3 hrs/ha	675.7	3 hrs/ha	675.7	3 hrs/ha	675.7	4 l/hr (56.3 MJ/l)
3	Fertilizer							
	i. N	60 kg	3636.0	20 kg	1212.0	60 kg	3636.0	60.6 MJ/kg
	ii. P	40 kg	444.0	40 kg	444.0	40 kg	444.0	11.1 MJ/kg
	iii. K	20 kg	134.0	20 kg	134.0	20 kg	134.0	6.7 MJ/kg
4	Herbicides and application							
	I. Pre-sowing	1.5 l	180.0	1.5 l	180.0	1.5 l	180.0	120 MJ/kg SC*
	II. Post-emergence	1.5 l	180.0	0	0.0	0	0.0	120 MJ/kg SC*
	iii. Application (8 hrs/day)	2 laborers*	31.4	1 laborer	15.7	1 laborer	15.7	1.96 MJ/man-hr
5	Gap filling and thinning	0	0.0	3 laborers	47.0	3 laborers	47.0	1.96 MJ/man-hr
6	i. Insecticide	0	0.0	1 l	120.0	1 l	120.0	120 MJ/kg SC*
	ii. Application	0	0.0	1 laborer	15.7	1 laborer	15.7	1.96 MJ/man-hr
7	i. Irrigation amount	1 irrigation	3.0	1 row irrigation	3.0	1 row irrigation	3.0	11.93 MJ/KWh (0.37MJ/hr)
	ii. Application	1 laborer	15.7	1 laborer	15.7	1 laborer	15.7	1.96 MJ/man-hr
8	Bird watching (15 days)	15 laborers	235.2	15 laborers	235.2	15 laborers	235.2	1.96 MJ/man-hr
9	Harvesting	10 laborers	156.8	8 laborers	125.6	10 laborers	156.8	1.96 MJ/man-hr
10	Threshing	5 laborers	78.4	3 laborers	47.0	5 laborers	78.4	1.96 MJ/man-hr
	Total		7534.2		4446.6		5857.2	
B. Inputs (Variable cost)								
1	Crop residues							
	i. Amount	5.0 t /ha dry mass	62500.0	5.0 t /ha dry mass	62500.0	5.0 t /ha dry mass	62500.0	12.5 MJ/kg
	ii. Application	3 laborers	47.0	3 laborers	47.0	3 laborers	47.0	1.96 MJ/man-hr
	Total		62547.0		62547.0		62547.0	
2	Leucaena twigs							
	i. Amount (dry biomass)	3.5 t/ha	43750.0	3.5 t/ha	43750.0	3.5 t/ha	43750.0	12.5 MJ/kg
	ii. Application	10 laborers	156.8	10 laborers	156.8	10 laborers	156.8	1.96 MJ/man-hr
	Total		43906.8		43906.8		43906.8	
C. Output								
1	Main product (all crops except oilseeds)						14.7 MJ/kg (25 MJ/kg in oilseeds)	
2	By-product (all crops)						12.5 MJ/kg	

SC* = Super chemicals; *8 hours/day **Energy co-efficient - Source: Devasenapathy et al. (2009)