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Carbon Footprint Assessment and Energy Budgeting of Different Annual and Perennial Forage Cropping Systems: A Study from the Semi-Arid Region of Karnataka, India

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Abstract: Efficient use of available resources in agricultural production is important to minimize carbon footprint considering the state of climate change. In this context, the current research was conducted to identify carbon and energy-efficient fodder cropping systems for sustainable livestock production. Annual monocropping, perennial monocropping, annual cereal + legume intercropping and perennial cereal + legume intercropping systems were evaluated by employing a randomized complete block design with three replications under field conditions. The lucerne (*Medicago sativa* L.) monocropping system recorded significantly lower carbon input (274 kg-CE ha^{-1} $year^{-1}$) and showed higher carbon indices viz., carbon sustainability index (165.8), the carbon efficiency ratio (166.8) and carbon efficiency (347.5 kg kg-CE^{-1}) over other systems. However, higher green fodder biomass led to statistically higher carbon output (78,542 kg-CE ha^{-1} $year^{-1}$) in the Bajra–Napier hybrid (*Pennisetum glaucum* × *Pennisetum purpureum*) + lucerne perennial system. Similar to carbon input, lower input energy requirement (16,106 MJ ha^{-1} $year^{-1}$) and nutrient energy ratio (25.7) were estimated with the lucerne perennial system. However, significantly higher energy output (376,345 and 357,011 MJ ha^{-1} $year^{-1}$) and energy indices viz., energy use efficiency (13.3 and 12.2), energy productivity (5.8 and 5.3 kg MJ^{-1}), net energy (327,811 and 347,961 MJ ha^{-1} $year^{-1}$) and energy use efficiency (12.3 and 11.2) were recorded with Bajra–Napier hybrid + legume [lucerne and cowpea (*Vigna unguiculata* (L.) Walp.)] cropping systems, respectively. However, these systems were on par with the lucerne monocropping system. Additionally, Bajra–Napier hybrid + legume [cowpea, sesbania (*Sesbania grandiflora* (L.) Pers.) and lucerne] cropping systems also showed higher human energy profitability. Concerning various inputs' contribution to total carbon and energy input, chemical fertilizers were identified as the major contributors (73 and 47%), followed by farmyard manure (20 and 22%) used to cultivate crops, respectively, across the cropping systems. Extensive use of indirect (82%) and non-renewable energy sources (69%) was noticed compared to direct (18%) and renewable energy sources (31%). Overall, perennial monocropping and cereal + legume cropping systems performed well in terms of carbon and energy efficiency. However, in green biomass production and carbon and energy efficiency, Bajra–Napier hybrid + legume (lucerne and cowpea) cropping systems were identified as the best systems for climate-smart livestock feed production.

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1. Introduction

Agricultural productivity and profitability assessment in terms of carbon footprint and energy budgeting is essential for efficient utilization and conserving available natural resources [1,2]. Reducing carbon footprint and efficient energy use in agricultural systems are important for sustainability [3]. Carbon equivalent greenhouse gas (GHG) emissive inputs and energy consumption are consistently increasing in agricultural systems to meet the increasing food and fodder needs of human and livestock populations. These include excessive use of various inputs such as fertilizers, chemicals, fossil fuel-driven farm machinery, electricity and more [4–6]. According to the Intergovernmental Panel on Climate Change (IPCC), agriculture, forestry and other land use activities accounted for approximately 23% of total anthropogenic GHG emissions during 2007–2016, i.e., 12.0 ± 2.9 Gt CO_2 equivalent per year [7,8].

Being an agricultural-based economy, India's food grain production has increased significantly from 522 kg ha^{-1} in the 1950 s to 2233 kg ha^{-1} in 2018–2019 [9]. Similarly, food grain production has increased from 52 million tons in 1951–1952 to 284.95 million tons in 2018–2019 [10]. Many studies have reported that fertilizer application is a vital component in achieving higher food grain production in India [11,12]. The average fertilizer consumption in India was 28 kg ha^{-1} during 1977–78, and it increased to 133.1 kg ha^{-1} during 2018–2019 ([13], Agricultural Statistics at a Glance, Ministry of Agriculture and Farmers Welfare, Government of India, 2020). This scenario of fertilizer consumption is almost similar to that of the world's fertilizer consumption patterns, i.e., 71 kg ha^{-1} of arable land in 1976 to 136.8 kg ha^{-1} in 2018 (Food and Agriculture Organization, 2020). On the other hand, farm mechanization is gaining importance in Indian agriculture due to shrinking agricultural labor and the availability of draught animals. In India, the contribution of animal power to agriculture has decreased from 93% (1960–1961) to 12.6% (2010–11), while contributions from mechanical and electrical sources have increased from 7 to 87.4% and will continue to increase in the future as animal power declines to 4.1% by 2032–2033 [14]. GHG emissions from the agriculture sector increased by 25% during 1990–2014, mainly due to emissions from synthetic fertilizers (47%) and enteric fermentation from livestock (30%) [15]. In this context, it is necessary to comprehensively analyze the nexus of agricultural production systems with different cultivation processes and their carbon emissions and energy use.

Energy forms an integral part of successful crop production in agriculture. Since the green revolution, commercial energy sources (e.g., fossil fuels), insecticides and machinery have played a significant role in achieving higher agricultural production besides posing a threat to the environment [16–18]. Agricultural farms use energy from various sources, including direct, indirect (chemicals, irrigation and machinery), renewable and non-renewable sources [19]. As a result, identifying energy-efficient inputs and production systems will aid in reducing environmental risks and, as a consequence, promote sustainable agriculture through natural resource conservation [18,20]. However, several studies have reported higher crop yields with increasing energy input consumption while reducing energy use efficiency and energy profitability [21,22]. In this context, the energy budgeting of different crop cultivation processes helps to identify inefficient farm practices and inputs, further providing an opportunity for farm planners and policymakers to devise strategies to improve efficiency. Many researchers have already determined the carbon indices viz., carbon sustainability index and carbon efficiency ratio, and energy indices viz., energy use efficiency, energy productivity, energy profitability, nutrient energy ratio and human energy profitability in many field crops such as paddy, wheat, maize, eggplant, apple, sugar beet, rice-wheat cropping systems, crop–livestock–poultry integrated farming systems, etc., for identifying the best cultivation practices and production systems in terms of carbon and energy utilization, but these are rarely documented regarding fodder crop cultivation throughout the world [1–6].

In India, livestock forms the backbone of the agriculture sector, contributing 24.7% to the total agricultural gross domestic product annually [23]. The consistent increase in the livestock population is creating higher demand for fodder biomass as fodder cultivation is limited to 4% of the cropped area in India [24]. Further increasing the human population results in the expansion of area under commercial food crops to meet their food and nutritional requirements. As of 2019 in India, there is a shortage of 11.2% green fodder, 23.4% dry fodder and 28.9% concentrate feeds [25]. Thus, there is a need to achieve higher fodder production through increasing productivity within the available area for fodder cultivation. Adoption of cropping systems, particularly cereal + legume cropping systems, will help to achieve higher productivity per unit area and time by complementary nature of the component crops [23,24]. Generally, cereal fodder crops are rich in carbohydrates, and legume crops are a good source of protein; hence, a mixture of these fodder will further help to achieve nutritional rich fodder for livestock in the place of costly concentrate feeds [26]. Many studies have reported good quality of fodder with higher productivity under cereal–legume intercropping systems across India [27,28] and abroad [29–31]. However, in most studies, they documented their performance only in terms of productivity and fodder quality. In the present scenario, the selection of cropping systems should not be limited to their productivity or economic profitability, but they should also be assessed in terms of carbon footprint and energy consumption patterns to achieve long-term sustainability [32]. Input–output analysis of carbon and energy has been rarely evaluated and documented in fodder cropping systems. Thus, the main objective of this research was to estimate carbon footprint and energy budgeting analysis under different annual and perennial fodder cropping systems to identify the most efficient and productive system.

2. Materials and Methods

2.1. Experimental Site

This research was conducted throughout 2018–19 and 2019–20 (June–May) at the Zonal Agricultural Research Station, Vishweshwaraiah Canal Farm, Mandya, Karnataka, India (12°45′ to 13°57′ North latitude and 76°45′ to 78°24′ East longitude and an altitude of 695 m above mean sea level). Prevailed weather conditions and chemical properties of the study site are presented in Table 1.

Table 1. Chemical properties and weather conditions of the experimental site during the study.

Parameter	Values Recorded	
Soil type	Red sandy loam	
pH	7.45	
Electrical conductivity (EC)	0.38 ds m^{-1}	
Organic carbon	5.5 g kg^{-1}	
Available Nitrogen	118.5 mg kg^{-1}	
Available Phosphorus	22 mg kg^{-1}	
Available Potassium	72.5 mg kg^{-1}	
	Prevailed weather conditions	
	During 2018–2019	During 2019–2020
Rainfall	520.7 mm	912.7 mm
Temperature		
Maximum	35.5 °C (May)	36 °C (June)
Minimum	17 °C (January)	16.3 °C (December)
Relative humidity		
Maximum	95% (August)	92% (October)
Minimum	53% (May)	35% (March)

2.2. Fodder Cropping System

In our study, we investigated 15 different fodder cropping systems, comprising 5 annual monocropping, 4 perennial monocropping, 2 annual cereals + legume intercropping and 4 perennial cereals + legume intercropping systems. The statistical design used was Randomized Complete Block Design (RCBD) with three replications. Details of the different systems, varieties and spacing adopted in the experiment are presented in Table 2. Annual cropping systems were sown during each season, while perennial systems were sown only once at the initial establishment of the systems. All management practices were followed as per the package of practices developed by the University of Agricultural Sciences, Bangalore, Karnataka. As per the recommendation, farmyard manure (FYM) was applied three weeks before sowing (Supplementary Table S1). Chemical fertilizers were applied at the sowing time with a full dose of phosphorus (P) and potassium (K) (Supplementary Table S1). In annual monocropping and intercropping systems, 50% nitrogen (N) was supplied as a basal dose, with the remainder applied 30 days after sowing (DAS) as a top dress. In perennial monocropping and intercropping systems, 10% N was supplied as a basal dose at the time of sowing, with the remainder applied in equal splits after each harvest.

Table 2. Different fodder cropping systems adopted in the experiment.

Treatments	System Type	Treatment Details	Variety/Hybrid	Spacing
T1	Annual monocropping	Maize–Maize–Maize	African Tall	30 × 10 cm
T2		Sorghum–Sorghum–Sorghum	Sudex Chari-1	
T3		Oat–Oat–Oat	OS-6	
T4		Pearl millet–Pearl millet–Pearl millet	BAIF bajra-1	
T5		Cowpea–Cowpea–Cowpea	MFC-09-1	
T6	Perennial monocropping	Bajra–Napier hybrid	BNH-10	90 × 60 cm
T7		Lucerne	RL-88	30 × 10 cm
T8		Desmanthus	Co-1	
T9		Sesbania	Local	
T10	Annual cereal + legume intercropping (3:1 row proportion)	Maize + Cowpea–Oat + Cowpea–Pearl millet + Cowpea	-	30 × 10 cm
T11		Sorghum + Cowpea–Maize + Cowpea–Pearl millet + Cowpea	-	
T12	Perennial cereal + legume intercropping (2:8 row proportion)	Bajra–Napier hybrid + Cowpea	-	Main crop-90 × 45 cm, intercrop-30 × 10 cm
T13		Bajra–Napier hybrid + Lucerne	-	
T14		Bajra–Napier hybrid + Desmanthus	-	
T15		Bajra–Napier hybrid + Sesbania	-	

Note: Same varieties/hybrids were used under intercropping systems as that of monocropping.

2.3. Fodder Yield Measurement

All crops were manually harvested individually with a sickle based on the growth and development stage in each treatment. Annual crops such as maize (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench.] were harvested at the milking and full blooming stages, respectively, while oats (*Avena sativa* L.), pearl millet (*Pennisetum glaucum* L.) and cowpea were harvested at 50% flowering. Regarding perennials viz., lucerne, desmanthus [*Desmanthus virgatus* (L.) Willd.], sesbania and the Bajra–Napier hybrid, an initial cut was taken at 60, 90, 180 and 70 DAS, respectively, at a 15–20 cm height from the ground level and succeeding cuts were made at 25–30, 45–50, 45–50 and 35–45 days, based on their growth. The green fodder yield was weighed according to the treatment and expressed in kilograms per hectare (kg ha^{-1}) at each harvest. The total pooled yield of the cropping systems was presented, and the same was used to estimate different carbon and energy indices.

2.4. Carbon Analysis

Total GHG emission from the various input components was determined by multiplying their specific carbon coefficients (Table 3) and expressed in terms of carbon equivalent (CE) per unit area and time (CE ha^{-1} year^{-1}) [33,34]. Total carbon output was derived by adding both above-ground (green fodder) and below-ground (root) biomass of the fodder crops [35]. The root biomass was calculated from the shoot to root ratio of respective fodder crops. The total carbon present in the biomass was determined by multiplying the biomass by 40%, as it was assumed that biomass contains 40% carbon [36]. The different carbon indices were estimated for all the cropping systems using the following equations [36–38].

$$Carbon\ input\ (Kg - CE/ha/year) = (Sum\ of\ total\ GHG\ emissions\ in\ CO_2\ equivalents) \times \frac{12}{44} \quad (1)$$

$$Carbon\ output\ (kg - CE/ha/year) = Total\ biomass \times 0.4. \quad (2)$$

$$Carbon\ sustainability\ index = \frac{(Carbon\ output - Carbon\ input)}{Carbon\ input}. \quad (3)$$

$$Carbon\ efficiency\ ratio = \frac{Carbon\ output}{Carbon\ input}. \quad (4)$$

$$Carbon\ efficiency\ (kg/kg - CE) = \frac{Fodder\ yield\ (kg/ha/year)}{Carbon\ output\ (kg - CE/ha/year)}. \quad (5)$$

Table 3. Emission factor of different inputs used in the estimation of total carbon input.

Input Source	Emission Factor	Reference
Fertilizers	Nitrogen: 1.74 t-CE t^{-1} N fertilizer Phosphorus: 0.2 t-CE t^{-1} P fertilizer Potash: 0.15 t-CE t^{-1} K fertilizer	[39,40]
N fertilizer induced N_2O	1.28 t-CE t^{-1} N fertilizer	[41]
Farmyard Manure (FYM)	0.007×10^3 t-CE t^{-1} FYM	
Pesticides	6.3×10^{-3} t-CE t^{-1} herbicide 5.1×10^{-3} t-CE t^{-1} insecticide 3.9×10^{-3} t-CE t^{-1} fungicide	[33]
Electricity	7.25×10^{-5} t-CE kWh^{-1} energy	
Diesel	7.17×10^{-4} t-CE L^{-1} diesel	[34]

2.5. Energy Analysis

Energy requirement for the cultivation of different fodder cropping systems was quantified using various input components consumed and energy outputs produced from each cropping system. All the physical input and output components were converted into their respective energy equivalents by multiplying them by their corresponding energy co-efficient (Table 4). Further, the following energy indices were estimated for identifying energy-efficient fodder cropping systems [37,42–44].

$$Energy\ use\ efficiency = \frac{Total\ energy\ ouput\ (MJ/ha/year)}{Total\ energy\ input\ (MJ/ha/year)}. \quad (6)$$

$$Energy\ productivity\ (kg/MJ) = \frac{Fodder\ yield\ (kg/ha/year)}{Total\ energy\ input\ (MJ/ha/year)}. \quad (7)$$

$$Specific\ productivity\ (MJ/kg) = \frac{Total\ energy\ input\ (MJ/ha/year)}{Fodder\ yield\ (kg/ha/year)}. \quad (8)$$

$$Net\ energy\ (MJ/ha/year) = Total\ energy\ ouput\ (MJ/ha/year) - Total\ energy\ input\ (MJ/ha/year). \quad (9)$$

$$Energy\ profitability = \frac{Net\ energy\ (MJ/ha/year)}{Total\ energy\ input\ (MJ/ha/year)}. \quad (10)$$

$$Nutrient\ energy\ ratio = \frac{Total\ energy\ ouput\ (MJ/ha/year)}{Nutrient\ energy\ input\ (MJ/ha/year)}. \quad (11)$$

$$Human\ energy\ profitability = \frac{Total\ energy\ ouput\ (MJ/ha/year)}{Human\ energy\ input\ (MJ/ha/year)}. \quad (12)$$

$$Direct\ energy\ (MJ/ha/year) = Labour + Fuel + Electricity. \quad (13)$$

$$Indirect\ energy\ (MJ/ha/year) = Fertilizers + Machinery + Chemicals + Irrigation + Seed. \tag{14}$$

$$Renewable\ energy\ (MJ/ha/year) = Labour + FYM + Irrigation\ water. \tag{15}$$

$$Non-renewable\ energy\ (MJ/ha/year) = Fertilizers + Machinery + Fuel + Chemicals + Electricity + Seed. \tag{16}$$

Table 4. Energy equivalents of inputs and outputs of forage cultivation.

Input	Unit	Equivalent Energy (MJ Unit^{-1})	Reference
Labor			
a. Male labor	Hour	1.96	[45]
b. Female labor	Hour	1.57	[45]
Diesel fuel	Liter	56.31	[46]
Machinery	Hour	62.7	[47]
Chemicals	Kilogram	120	[4]
Chemicals	Liter	102	[4]
Fertilizers	Kilogram		
a. Nitrogen		66.14	[48]
b. Phosphorus		12.44	[48]
c. Potassium		11.15	[48]
d. Micronutrients		120	[49]
Farmyard manure	Kilogram	0.3	[50]
Irrigation	Cubic meter	1.02	[21]
Electricity	Kilowatt hour	3.6	[51]
Seeds	Kilogram	15.7	[51]
Output			
Green fodder yield	Kilogram	2.30	[52]

2.6. Statistical Analysis

The pooled data were subjected to Duncan's Multiple Range Test (DMRT) to determine the significant difference ($p < 0.05$) between the cropping systems using OPSTAT, a statistical software package developed by Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India [53].

3. Results

3.1. Total Carbon Input and Share of Different Inputs

In general, perennial fodder cropping systems consumed less agricultural inputs and resulted in lower carbon input. They also showed higher carbon output due to large green fodder biomass production compared to other cropping systems involving annual crops. The monocropped lucerne perennial cropping system showed considerably lower carbon input, followed by sesbania and desmanthus perennial systems. However, monocropped maize recorded numerically higher carbon input throughout the year followed by annual cereal–legume intercropping systems viz., fodder maize + cowpea–fodder oat + cowpea–pearl millet + cowpea and fodder sorghum + cowpea–fodder maize + cowpea–pearl millet + cowpea (Table 5).

Table 5. Carbon input, output and its indices under different cropping systems involving annual and perennial fodder crops. For treatment details see Table 2.

Treatments	GFY (kg ha^{-1} Year^{-1})	Carbon Input (kg-CE ha^{-1} Year^{-1}) *	Carbon Output (kg-CE ha^{-1} Year^{-1})	CSI	CER	Carbon Efficiency (kg kg-CE^{-1})
T1	104,658 ^{fgh}	1419.5	50,236 ^{fgh}	34.4 ^{g}	35.4 ^{g}	73.7 ^{g}
T2	90,650 ^{ghi}	1010.3	43,512 ^{ghi}	42.1 ^{g}	43.1 ^{g}	89.7 ^{g}
T3	82,658 ^{i}	1247.5	39,676 ^{i}	30.8 ^{g}	31.8 ^{g}	66.3 ^{g}
T4	85,358 ^{hi}	1247.5	40,972 ^{hi}	31.8 ^{g}	32.8 ^{g}	68.4 ^{g}
T5	77,817 ^{i}	511.1	37,352 ^{i}	72.1 ^{f}	73.1 ^{f}	152.2 ^{f}
T6	126,150 ^{cde}	760.7	60,552 ^{cde}	78.6 ^{ef}	79.6 ^{ef}	165.8 ^{ef}
T7	95,217 ^{fghi}	274.0	45,704 ^{fghi}	165.8 ^{a}	166.8 ^{a}	347.5 ^{a}
T8	79,608 ^{i}	400.9	38,212 ^{i}	94.3 ^{cde}	95.3 ^{cde}	198.6 ^{cde}
T9	95,992 ^{fghi}	397.7	46,076 ^{fghi}	114.9 ^{b}	115.9 ^{b}	241.4 ^{b}
T10	110,268 ^{efg}	1412.9	52,928 ^{efg}	36.5 ^{g}	37.5 ^{g}	78.0 ^{g}
T11	115,325 ^{def}	1380.7	55,356 ^{def}	39.1 ^{g}	40.1 ^{g}	83.5 ^{g}
T12	155,222 ^{ab}	763.9	74,507 ^{ab}	96.5 ^{cd}	97.5 ^{cd}	203.2 ^{cd}
T13	163,628 ^{a}	763.9	78,542 ^{a}	101.8 ^{bc}	102.8 ^{bc}	214.2 ^{bc}
T14	131,059 ^{cd}	763.9	62,908 ^{cd}	81.3 ^{def}	82.3 ^{def}	171.6 ^{def}
T15	144,002 ^{bc}	763.9	69,121 ^{bc}	89.5 ^{cde}	90.5 ^{cde}	188.5 ^{cde}

Note: GFY, Green fodder yield; CSI, Carbon sustainability index; CER, Carbon efficiency ratio; *, Statistically not analyzed. Values with different alphabets are significantly different from each other as per the DMRT at $p < 0.05$.

The contribution from various inputs used to cultivate different fodder crops will vary according to their carbon emission potential. In this study, the important inputs considered were fertilizers, FYM, pesticides, fuel and irrigation water. Among these inputs, fertilizers accounted for a major share (73%), followed by FYM (20%), diesel (6%) and irrigation (1%). However, due to the very low amount of pesticide usage, it showed extremely low values (almost zero) contribution to the carbon input in our study (Figure 1)

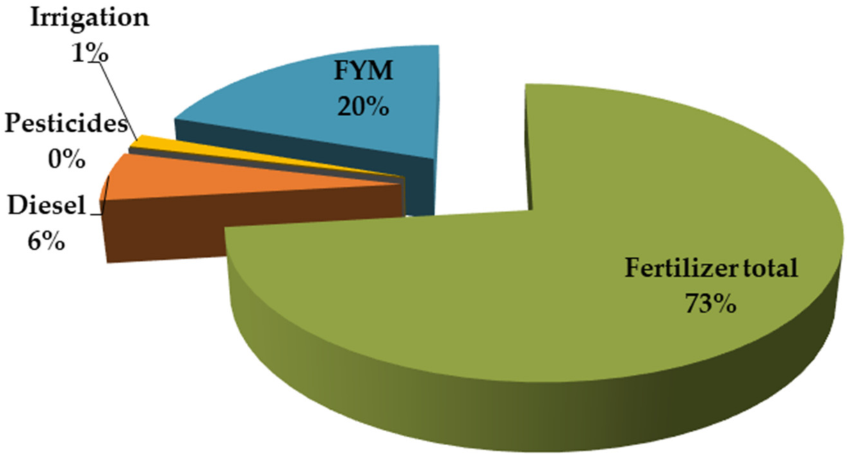

Figure 1. Overall mean share (%) of inputs used in the carbon footprint estimation of different fodder cropping systems.

3.2. Total Carbon Output and Carbon Indices

With respect to carbon output, significantly higher green fodder biomass with Bajra–Napier hybrid + lucerne and Bajra–Napier hybrid + cowpea systems resulted in statistically higher carbon output over other cropping systems. Further, Bajra–Napier hybrid + sesbania and Bajra–Napier hybrid + desmanthus systems closely followed the above-mentioned cropping systems. In this study, reduced carbon output with both annual (maize, sorghum, pearl millet, oats and cowpea) and perennial (Bajra–Napier hybrid, lucerne, desmanthus and sesbania) monocropping systems by 36, 45, 48, 50, 52, 23, 42, 51, 41%, respectively, were noticed over the superior Bajra–Napier hybrid + lucerne system (Table 5).

To identify carbon-efficient fodder cropping systems, different carbon indices, viz., carbon sustainability index (CSI), carbon efficiency ratio (CER) and carbon efficiency (CE), were estimated and presented in Table 5. Among the systems, the perennial lucerne cropping system was identified as the best carbon-efficient system with higher CSI, CER and carbon efficiency, which was closely followed by the sesbania monocropping, Bajra–Napier hybrid + lucerne and Bajra–Napier hybrid + cowpea perennial cropping systems. The above statement indicates the efficient utilization of different carbon emitting inputs in biomass production in those cropping systems. However, inefficient input utilization and higher carbon-emitting inputs consumption lead to lower CSI, CER and carbon efficiency in seasonal cereal–legume intercropping systems (fodder maize + cowpea–fodder oat + cowpea–pearl millet + cowpea and fodder sorghum + cowpea-fodder maize + cowpea–pearl millet + cowpea) as well as annual cereal (maize, sorghum, oats and pearl millet) monocropping systems. Overall, the carbon indices ranged from 30.8–165.8 (CSI), 31.8–166.8 (CER) and 66.3–347.5 kg kg^{-1}-CE^{-1} (carbon efficiency), with the highest in the Bajra–Napier hybrid + lucerne perennial system and the lowest in the oats monocropping system (Figure 2).

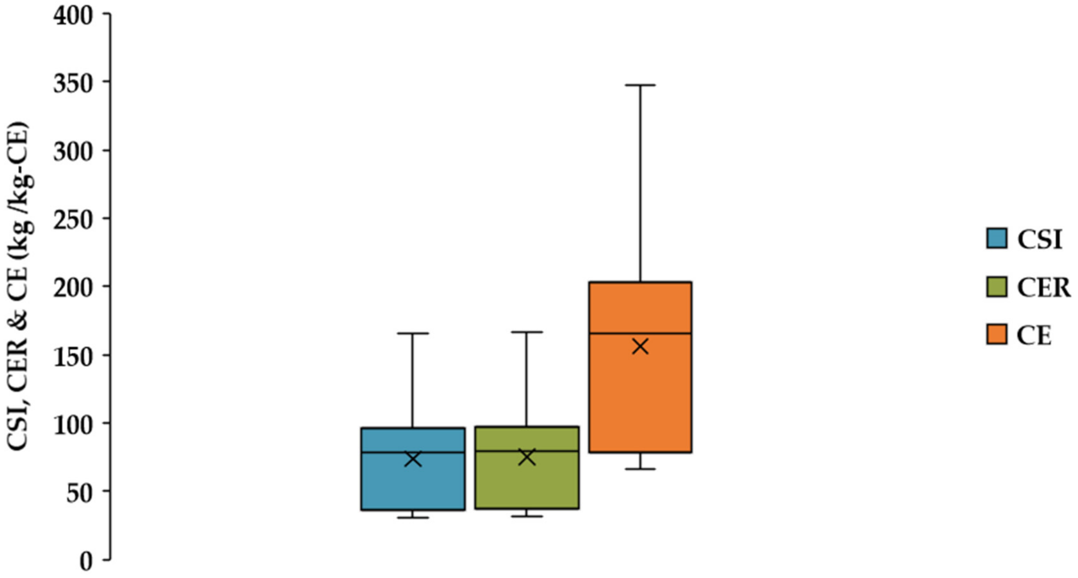

Figure 2. Box and Whisker plot of overall mean carbon indices under different fodder cropping systems. CSI, Carbon Sustainability Index; CER, Carbon Efficiency Ratio; CE, Carbon Efficiency. X-axis indicates carbon indices; the error bar is the range of respective values of the indices.

3.3. Total Energy Input and Share of Different Inputs

Similar to the carbon input consumption pattern, lower total energy input utilization was observed in perennial fodder cropping systems than in annual systems. Among the systems, numerically, the lowest energy consumption was noticed with lucerne, followed by desmanthus and sesbania perennial systems. Among the annual systems, the cropping system involving cowpea recorded lower input energy consumption than other annual systems in the study. There was a 76, 47, 47 and 11% increase in the total energy input of the systems when lucerne, desmanthus, sesbania and cowpea were intercropped with the Bajra–Napier hybrid compared to monocropping. However, the highest energy consumption was noticed with the maize monocropping system, and the tune of increase was 226% over the lowest consumed lucerne system (Table 6).

Table 6. Energy input, output and its indices under different cropping systems involving annual and perennial fodder crops.

Treatments	Energy Input * (MJ ha^{-1} Year^{-1})	Energy Output (MJ ha^{-1} Year^{-1})	Energy Use Efficiency	Energy Productivity (kg MJ^{-1})	Specific Productivity (MJ kg^{-1})	Net Energy (MJ ha^{-1} Year^{-1})	Energy Profitability
T1	52,466	240,714 ^{fgh}	4.6 ^{f}	2.0 ^{f}	0.5 ^{ab}	1,882,481 ^{def}	3.61 ^{f}
T2	38,606	208,495 ^{ghi}	5.4 ^{ef}	2.3 ^{ef}	0.43 ^{bc}	1,698,891 ^{def}	4.41 ^{ef}
T3	46,550	190,114 ^{i}	4.1 ^{f}	1.8 ^{f}	0.57 ^{a}	1,435,641 ^{f}	3.11 ^{f}
T4	42,912	196,324 ^{hi}	4.6 ^{f}	2 ^{f}	0.5 ^{ab}	1,534,121 ^{f}	3.61 ^{f}
T5	26,230	178,978 ^{i}	6.8 ^{e}	3.0 ^{e}	0.36 ^{c}	1,527481 ^{f}	5.81 ^{e}
T6	29,030	290,145 ^{cde}	10.0 ^{cd}	4.3 ^{cd}	0.23 ^{d}	2,611,151 ^{c}	9.01 ^{cd}
T7	16,106	218,998 ^{fghi}	13.6 ^{a}	5.9 ^{a}	0.17 ^{d}	2,028,931 ^{de}	12.61 ^{a}
T8	19,276	183,099 ^{i}	9.5 ^{d}	4.1 ^{d}	0.24 ^{d}	1,638,231 ^{ef}	8.51 ^{d}
T9	19,466	220,781 ^{fghi}	11.3 ^{bc}	4.9 ^{bc}	0.21 ^{d}	2,013,141 ^{de}	10.31 ^{bc}
T10	50,272	253,616 ^{efg}	5.0 ^{f}	2.2 ^{f}	0.46 ^{b}	2,033,431 ^{de}	4.01 ^{f}
T11	48,935	265,247 ^{def}	5.4 ^{ef}	2.4 ^{ef}	0.431 ^{bc}	2,163,121 ^{d}	4.41 ^{ef}
T12	29,200	357,011 ^{ab}	12.2 ^{ab}	5.3 ^{ab}	0.191 ^{d}	3,278,111 ^{ab}	11.21 ^{ab}
T13	28,384	376,345 ^{a}	13.3 ^{a}	5.8 ^{a}	0.171 ^{d}	3,479,611 ^{a}	12.31 ^{a}
T14	28,408	301,435 ^{cd}	10.6 ^{bcd}	4.6 ^{bcd}	0.221 ^{d}	2,730,271 ^{c}	9.61 ^{bcd}
T15	28,552	331,204 ^{bc}	11.6 ^{bc}	5.0 ^{bc}	0.201 ^{d}	3,026,521 ^{bc}	10.61 ^{bc}

Note: *—Statistically not analyzed. Values with different alphabets are significantly different from each other as per the DMRT at $p < 0.05$.

The different inputs viz., fertilizers, FYM, human labor, machinery, diesel, chemicals, irrigation, electricity and seeds were computed for energy input calculations in different cropping systems. Among the various inputs, fertilizers accounted for the major share of 67%, which was followed by Diesel (17%). However, the contribution of human labor, machinery, chemicals, irrigation, electricity and seeds was $\leq$ 5% in the current study (Figure 3).

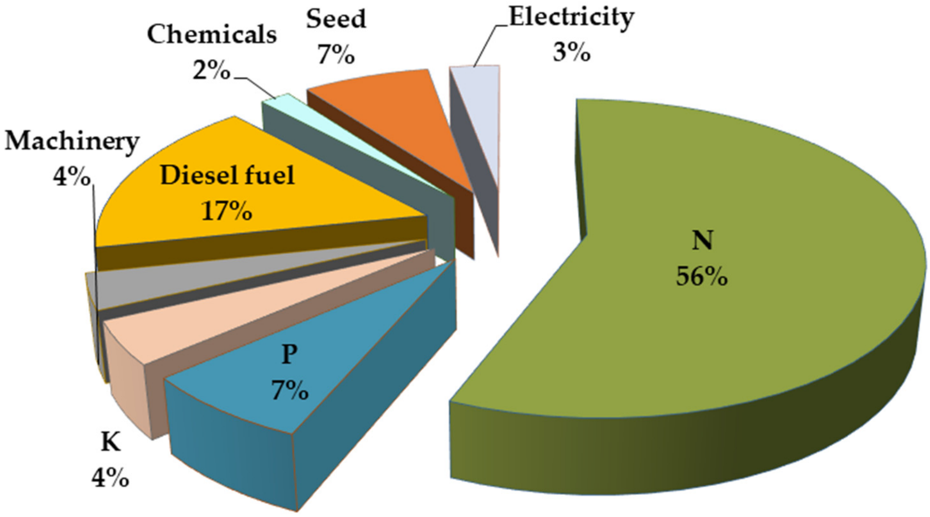

Figure 3. Overall mean share (%) of inputs in energy budgeting of different fodder cropping systems.

3.4. Total Energy Output and Energy Indices

Using the green biomass of different cropping systems, the total energy output and different energy indices were determined and presented in Table 6. A significantly higher energy output was recorded with the Bajra–Napier hybrid + lucerne and the Bajra–Napier hybrid + cowpea perennial cropping systems, and it was 110 and 100% higher than the lowest energy output recorded by the cowpea monocropping system. In the case of cropping systems involving monocropping of both cereal and legume fodder crops, the reduction in the energy output up to the magnitude of 23, 36, 45, 48, 49, 41, 42, 51 and 52% was noticed with the Bajra–Napier hybrid, maize, sorghum, pearl millet, oats, sesbania, lucerne, desmanthus and cowpea systems, respectively.

With respect to energy indices, the values ranged around 4.1–13.6 (energy use efficiency), 1.8–5.9 kg MJ^{-1} (energy productivity), 0.56–0.17 MJ kg^{-1} (specific productivity) and 3.1–12.6 (energy profitability) in the oats to lucerne monocropping systems (Figure 4). However, lucerne monocropping and the Bajra–Napier hybrid + legume (lucerne and cowpea) cropping systems were identified as the best energy-efficient systems as they showed significantly higher values of energy indices viz., energy use efficiency, energy productivity and energy profitability, respectively, over other systems in the study. Despite this, higher net energy was noticed with the Bajra–Napier hybrid + legume (lucerne and cowpea) cropping systems. On the other hand, the monocropping systems, mainly cereal (oats, pearl millet, maize, sorghum) fodder cropping systems, were noted as the most energy-inefficient systems in the current study because of their significantly lower energy indices values. With respect to specific products, all the perennial fodder cropping systems showed lower values ranging from 0.17 MJ kg^{-1} in the Bajra–Napier hybrid + lucerne system to 0.24 MJ kg^{-1} in the desmanthus system, which indicates that a lower amount of energy was consumed per unit quantity of fodder production in those cropping systems. On the other hand, significantly higher energy consumption per unit quantity of fodder production was recorded in oats, maize and pearl millet cereal monocropping systems.

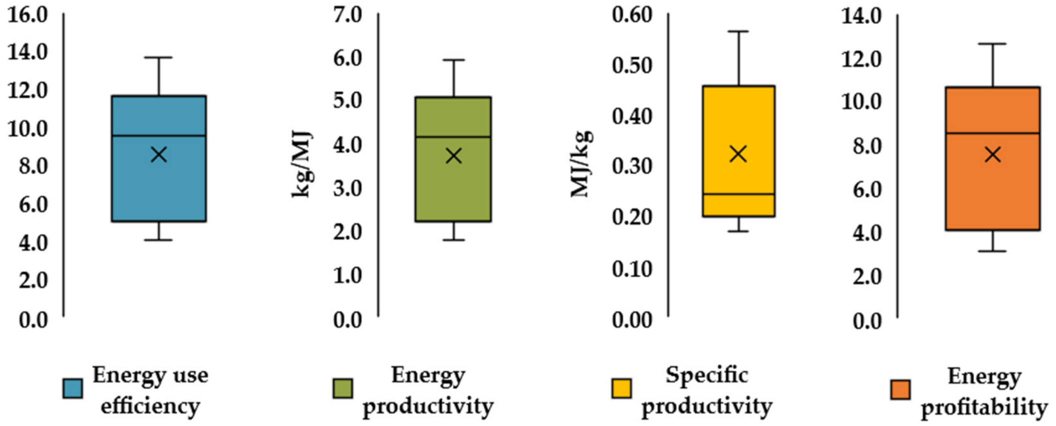

Figure 4. Box and Whisker plot of overall mean energy indices under different fodder cropping systems. Energy efficiency, energy productivity, specific productivity and energy profitability.

3.5. Nutrient Energy Ratio and Human Energy Profitability

In addition to carbon and energy indices, we also computed the nutrient energy ratio and human energy profitability for different systems, as illustrated in Figure 5. A statistically higher nutrient energy ratio of 25.6 was witnessed with lucerne perennial fodder cropping systems. Further, it was closely followed by the sesbania monocropping and Bajra–Napier hybrid + legume (lucerne, cowpea and sesbania) cropping systems. However, due to higher fertilizer consumption and lower energy output, a significantly lower nutrient energy ratio was registered in annual cereal monocropping systems (maize, sorghum, oats and pearl millet) and ranged from 5.9 in oats to 7.8 in the sorghum system. With respect to human energy profitability, higher energy output resulted in significantly higher human energy profitability with the Bajra–Napier hybrid + legume (cowpea, sesbania and lucerne) cropping systems. Contrastingly, more human labor requirement for perennial lucerne and desmanthus cultivation led to statistically lower human energy profitability of 111.8 and 114.4, respectively.

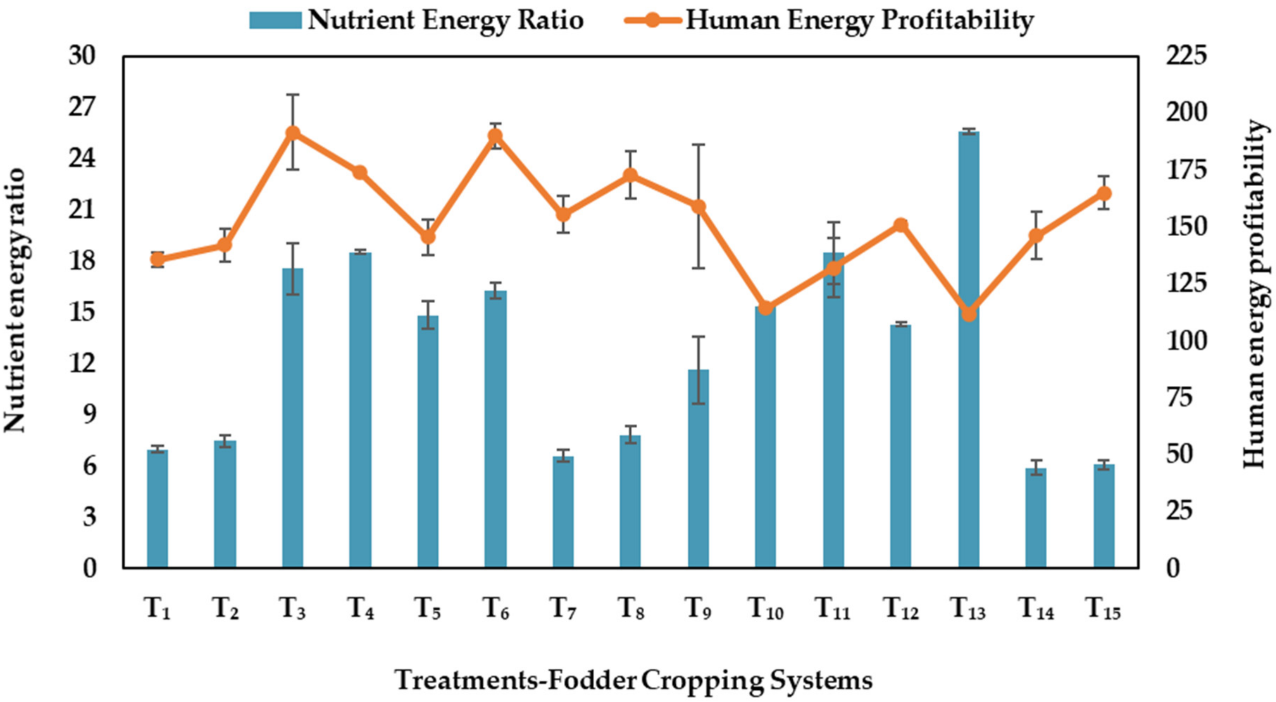

Figure 5. Nutrient energy ratio and human energy profitability under different fodder cropping systems. The bars in the figure indicate the standard error.

3.6. Energy Sources

To identify the potential contributors to the total input energy, various input sources, viz., direct, indirect, renewable, and non-renewable energy, were quantified for the different fodder cropping systems (Figure 6). For the total input energy, direct sources contributed 18%, while indirect energy sources accounted for a major share of 82%. Among direct sources, diesel used as a fuel for agricultural operations was identified as the major contributor, followed by human labor and electricity utilized power for irrigating crops (Figure 7). On the other hand, fertilizers (NPK) alone accounted for 58%, followed by FYM (27%) with respect to indirect energy sources. However, the contribution from seed, irrigation, machinery, and chemicals was very meager, i.e., $\leq$6% (Figure 8). In the case of renewable and non-renewable energy sources, the former accounted for 31%, while the latter accounted for 69% of the total input energy in the present study. FYM was identified as the major renewable energy contributor, followed by human labor and irrigation components (Figure 9). With respect to non-renewable energy sources, fertilizers (NPK) contributed 67%, followed by 17% with diesel fuel. However, machinery, chemicals, seed, and electricity contributed 4, 2, 7 and 3%, respectively (Figure 10). Among the different treatments, annual intercropping systems viz., fodder maize + cowpea–fodder oat + cowpea-pearl millet + cowpea and fodder sorghum + cowpea–fodder maize + cowpea-pearl millet + cowpea accounted for higher direct and renewable energy consumption while the sesbania perennial system consumed less. Similarly, concerning indirect and non-renewable energy consumption patterns they ranged from 44,486 and 40,389 MJ ha^{-1} in the monocropped maize system to 11,093 and 6617 MJ ha^{-1} in the lucerne perennial cropping system, respectively.

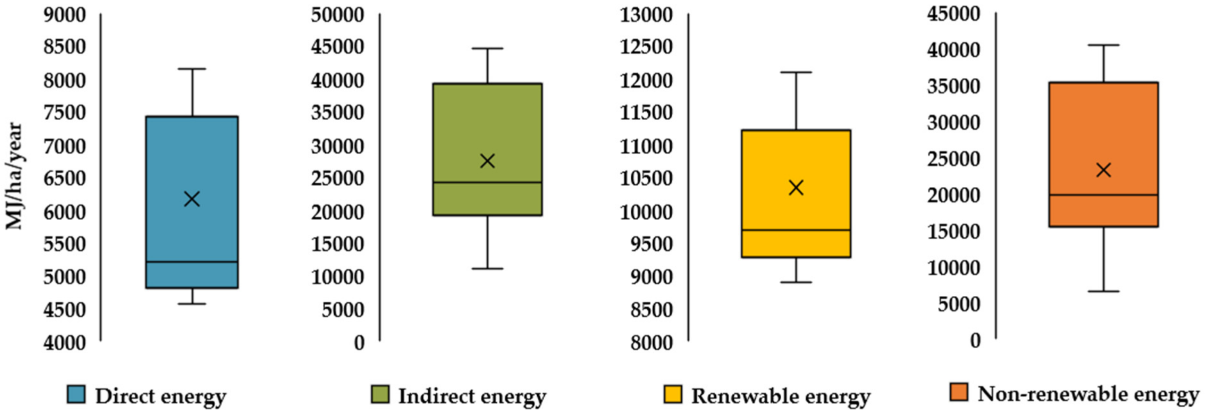

Figure 6. Overall mean energy sources of different fodder cropping systems. Direct energy, indirect energy, renewable energy, and non-renewable energy.

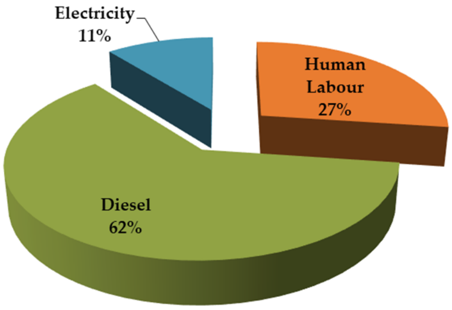

Figure 7. Overall mean share (%) of direct energy components under different fodder cropping systems.

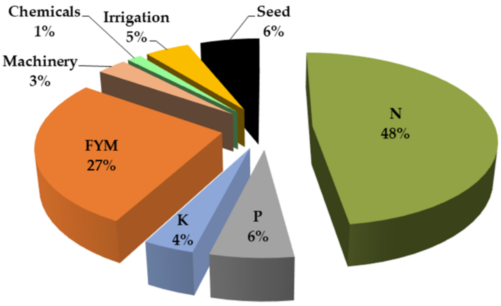

Figure 8. Overall mean share (%) of indirect energy components under different fodder cropping systems.

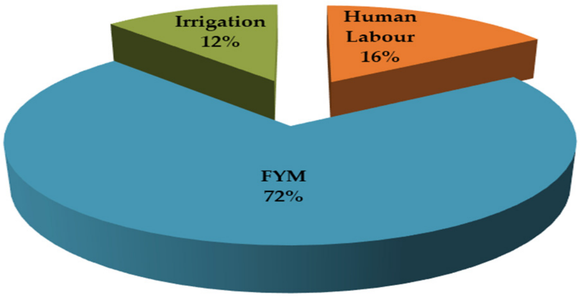

Figure 9. Overall mean share (%) of renewable energy components under different fodder cropping systems.

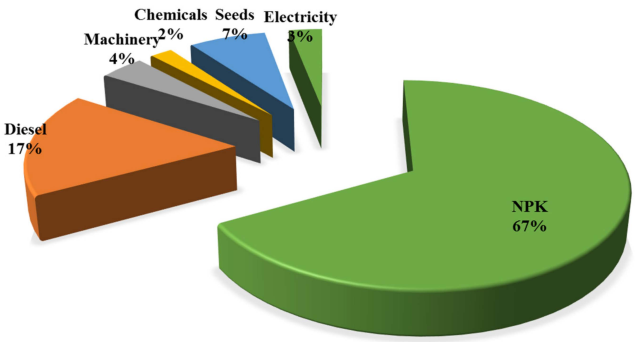

Figure 10. Overall mean share (%) of non-renewable energy components under different fodder cropping systems.

4. Discussion

4.1. Carbon Input, Output and Its Indices

With increasing atmospheric carbon dioxide levels, identifying ideal fodder cropping systems with high biomass production and low carbon equivalent input consumption is a challenge for sustainable livestock production. In the present study, among the 15 fodder cropping systems, legume monocropping systems consumed less carbon than cereal monocropping systems (Table 5). This can be attributed to reduced fertilizer application, particularly nitrogenous fertilizers, due to the atmospheric nitrogen fixation capacity of legume crops. The adoption of legume fodder crops improves native soil fertility by enhancing the nutrient and organic carbon levels through nitrogen fixation and the addition of crop residues and thereby reducing the fertilizer requirement for crops [54]. A lower amount of carbon dioxide equivalents per unit amount of forage dry matter production was reported in alfalfa (0.21 kg CO_2 kg^{-1}) than in corn and sorghum crops in the governorate of Sousse, Tunisia [55]. Similarly, greenhouse gas emissions per hectare of land use and per ton of product produced were lower in alfalfa and silage maize than in grain maize, wheat, and apple crops in Pingliang and Qingyang, cities of northwest China [56]. Interestingly, approximately 373 kg-CE ha^{-1} of carbon input reduction was noticed under cereal (Bajra–Napier hybrid) + legume (cowpea, lucerne, desmanthus and sesbania) perennial cropping systems due to lower fertilizer application than monocropped cereal crops.

In the current study, we also identified nutrient sources such as fertilizers and FYM as the significant carbon input contributors among the different inputs computed. Reduced fuel (diesel) consumption was noticed under perennial intercropping systems, as they are sown once a year but not every season, as in the case of annual crops. That, in turn, led to reduced agricultural operations under those systems and thereby lowered carbon input consumption in their cultivation. Gong et al. [57] reported chemical fertilizers as the significant contributors to carbon footprint (27.5–56.7%) in agricultural production systems. Further, they revealed a reduction in total carbon footprint with decreasing fertilizers usage in China. Similarly, Jiang et al. [58] reported a 49.5% contribution from nitrogen fertilizer alone to the total carbon footprint in rice cultivation in China. In addition, they noticed a positive correlation between the nitrogen fertilizer application rate and the total carbon footprint. Similar to our current results, Ma et al. [59] noticed a lower carbon footprint under maize–soybean and maize–forage legume (alfalfa or red clover) biannual rotation supplied with 100 kg N ha^{-1} by 41 and 46%, respectively, over monoculture maize supplied with 200 kg N ha^{-1}. Further, Liu et al. [60] stated that improving N fertilizer use efficiency can lower the carbon footprints of field crops as N fertilizer contributes 36 to 52% of the total emissions. Even in the USA, the application of both synthetic fertilizers and lime were identified as major contributors to carbon footprint in dairy feeds such as soybeans, alfalfa, corn and others [61]. Thus, GHG emissions can be effectively minimized by optimizing the N application rate, N form and fertilizer application method, and further using biochar, nitrification or urease inhibitors, as well as by adopting measures such as crop mulching, use of organic manures, green manuring crops and irrigation scheduling management [8,62,63]. Further, higher fruit yield, reduced input costs and reduced GHG emissions with higher carbon efficiency were reported in pomelo orchards when chemical fertilizers were combined and applied with organic manure in China [64].

The amount of carbon input consumption and carbon output production are key factors that determine the efficiency of different systems. Lower input consumption and higher output production aid in achieving higher efficiency. Higher total biomass (root + shoot) production resulted in significantly higher carbon output with Bajra–Napier hybrid + legume (cowpea, lucerne) systems. However, significantly higher carbon indices viz., CSI, CER and carbon efficiency, were observed with the lucerne monocropping system because of lower carbon input consumption. Similar to our results, higher carbon output and lower carbon input consumption led to higher carbon efficiency of 5.30, and CSI of 4.30 was previously reported in pigeonpea–wheat cropping systems [65]. On the other hand, Bajra–Napier hybrid + legume (cowpea, lucerne) systems also showed higher carbon indices mainly because of higher carbon output. Thus, these systems were identified as carbon-efficient systems as they consumed less carbon input per unit quantity of carbon output production in the current study.

4.2. Energy Input, Output and Its Indices

Currently, agri-food systems consume 30% of the world's available energy, with more than 70% occurring beyond the farm gate, and are responsible for nearly 20% of global greenhouse gas emissions [66]. Improvement in energy efficiency is generally considered the best strategy to reduce CO_2 emissions and further limit energy dependence in agriculture. In this regard, the identification of energy-efficient inputs and cropping systems is a primary concern in the current scenario of limited natural resource availability in the world. Similar to the carbon input and output, 30% higher energy output was noticed with perennial fodder cropping systems (both monocropping and intercropping) despite 43% lower energy input consumption over annual cropping systems. The above statement clearly indicates that perennial fodder cropping systems produced more output per unit quantity of input used and were identified as energy-efficient systems. Further, these results are evident by the higher energy use efficiency (9.5–13.6), energy productivity (4.1–5.9 kg MJ^{-1}) and energy profitability (8.5–12.6) in perennial fodder cropping systems compared to 4.1–6.8, 1.8–3.1, and 3.1–5.8 kg MJ^{-1} , respectively, in the case of annual fodder cropping systems. Perennial legume fodders have shown higher energy use efficiency and lower energy input requirement because of their lower demand for nitrogen fertilizers, as they meet part of their nitrogen requirement through the atmospheric nitrogen fixation process [67]. Similar to our study, Budzynski et al. [68] also reported energy use efficiency of 11.6 and 9.6 with perennial legume fodders of galega and alfalfa, respectively, at Olsztyn. Among the perennial systems, Bajra–Napier hybrid + legume (lucerne and cowpea) intercropping systems were identified as more energy efficient systems because of their higher net energy production along with higher green fodder production, which is much needed to meet India's current fodder crisis in order to feed the increasing livestock population. Higher energy output and energy use efficiency was obtained by introducing legume fodder crops as an intercrop with rice in place of the rice monocropping system due to higher grain and fodder yield in Odisha, India [54]. Prajapat et al. [32] also reported higher energy output (370.7×10^3 MJ ha^{-1}), net energy (331.9×10^3 MJ ha^{-1}), energy use efficiency (9.56), energy productivity (179.0 g MJ^{-1}) and profitability (8.6) with a soybean–chickpea–fodder sorghum cropping system due to higher biomass production. Even in an integrated farming system, green fodder cultivation (sorghum, cowpea, berseem and oats) showed higher energy use efficiency (7.66) followed by the field crops (5.06) and vegetables (1.51) than other components of the system [18].

External supply of nutrients in the form of fertilizers is a major source of plant nutrition and, to a certain extent, FYM in the present agricultural system. Further, the adoption of agricultural machinery for various tillage and transportation operations is consequently increasing the fuel consumption in agriculture production systems. In our study, we also identified fertilizers followed by FYM and diesel as major energy inputs to the total energy consumption by the cropping systems. Even Patel et al. [22] identified fuel, fertilizers and FYM as major contributors to the total input energy in kharif maize cultivation in the Panchmahal District of Gujarat, India. Mishra et al. [6] also reported fertilizer application as the highest energy consumption input (35.9%) in different fodder crops production in the Allahabad district of Utter Pradesh state. This signifies that by reducing these inputs by increasing their efficiency, we can further reduce the energy input required in any system and thereby achieve higher energy efficiency. The adoption of resource conservation practices, such as the introduction of in situ green manure crops (*Sesbania rostrata*) as part of integrated nutrient management in rice, have resulted in a decrease in energy input by 21% and, subsequently, an increase in energy productivity and energy use efficiency by 27 and 26%, respectively [69]. In Northwestern Italy, an increase in energy use efficiency by 31.4 and 32.7% was reported in integrated farming systems and low-input farming systems, respectively, compared to conventional farming systems in wheat–maize–soybean–maize rotation [70].

4.3. Nutrient Energy Ratio and Human Energy Profitability

To increase the productivity per unit land area under different cropping systems, it is imperative to supply nutrients externally through fertilizers in an adequate quantity to maintain the soil fertility along with organic sources [12,71]. Further, excess application of fertilizers leads to various adverse effects on the ecosystem besides increasing their contribution to carbon and energy input requirements in the production and thereby reducing the system's efficiency in terms of carbon, energy, and nutrients. Perennial legume monocropping systems (lucerne, sesbania and desmanthus) and Bajra–Napier hybrid + legume intercropping systems have shown higher nutrient productivity over other systems. Reduced nutrient application, particularly regarding nitrogen due to the atmospheric nitrogen-fixing capacity of legume crops, leads to a better nutrient energy ratio in said cropping systems over cereal cropping systems. In the case of legume crops viz., soybean, chickpea and mungbean, the contribution from fertilizers to the total energy input was less (12.1–17.3%). In contrast, it was comparatively higher in the case of cereal crops viz., wheat, potato, and fodder sorghum (33.1–35.1%), due to higher nutrient requirements [31].

Mechanical energy in the form of human labor is one of the most valuable inputs in agricultural production in the Indian context [72,73]. In our study, a greater number of human laborers engaged with fodder harvesting due to a greater number of harvests per year in the case of perennial cereal (Bajra–Napier hybrid) + legume (cowpea, lucerne, sesbania) cropping systems coupled with higher biomass production led to higher human energy profitability. Similarly, Parajuli et al. [74] also found that a higher frequency of harvesting, loading and transportation is associated with the cultivation of perennial crops in Denmark. This clearly indicates that these systems are not only productive in terms of biomass, but they also create employment for agricultural labor in addition to maintaining their efficiency in the production process. Prajapat et al. [32] reported higher human energy profitability of 105.2 due to higher labor consumption as well as subsequent higher biomass production with the soybean–chickpea–fodder sorghum cropping system in New Delhi, India.

4.4. Energy Sources

Current agricultural practices mainly rely on indirect and non-renewable energy sources such as fertilizers, pesticides, machinery, and fuel which contribute to GHG emissions and further accelerate climate change [75]. The use of fertilizers and diesel is the primary energy input for field crops. The energy input for irrigation, drying and/or storage is often important, but it is dependent on geographical location and the associated climate, as well as the intensity of the production system [76]. Sustainable agriculture aims to minimize the use of non-renewable energy sources and further promote the adoption of renewable energy sources such as naturally available organic nutrients, solar/wind energy, hydropower, biofuels, integrated nutrients, pest management etc. [77]. Generally, the energy input requirement will vary according to the crop species, soil conditions, nutrient requirement, pesticide usage, irrigated/rainfed condition, cultivation method, number of harvests etc. Indirect and non-renewable energy sources were identified as the major energy input sources in the cultivation of different fodder cropping systems in the current study, with fertilizers as the major contributors. Thus, the effective management of these components by increasing the nutrient use efficiency of fertilizers using the four R principles (right quantity, right time, right method, and right place of application) or soil test-based fertilizer application, energy (fuel) efficient machinery and the use solar energy driven machinery can further reduce their quantity and ultimately reduce the carbon and energy input requirements. Patel et al. [22] also reported indirect energy sources (54.56%) as major contributors to input energy over direct energy sources (45.44%). In China, in a study conducted by Li et al. [78], all cropping systems were found to depend on indirect (56.68–67.58%) and non-renewable energy input sources (80.67–98.38%) to a great extent. Even in European countries such as Portugal, Poland, the Netherlands, Greece, Germany and Finland, indirect energy consumption sits in the range of 50–72% in wheat production, with synthetic fertilizers as significant contributors [76]. However, compared to cereal cropping systems, perennial monocropping and intercropping systems have shown 45 and 52% reductions in indirect and non-renewable energy source use, roughly 46% on average, owing to comparatively lower fertilizer consumption. Thus, to attain sustainability, the contribution of renewable energy sources to input energy needs to be maximized in place of non-renewable energy sources in agricultural cropping systems [79–82].

5. Conclusions

In the present study, perennial monocropping systems, as well as Bajra–Napier hybrid + legume cropping systems, outperformed monocropping annual cereal and cereal + legume cropping systems in terms of biomass, carbon output and energy output. Particularly, lower carbon and energy input consumption led to achieving higher carbon indices and energy indices with lucerne monocropping and Bajra–Napier hybrid + legume (lucerne and cowpea) cropping systems. Higher energy requirement (0.43–0.57 MJ kg^{-1}) per unit quantity of fodder production was noticed in annual cereal crops compared to perennial monocropping as well intercropping systems (0.17–0.24 MJ kg^{-1}). Lower fertilizer recommendation, specifically nitrogen in the case of the lucerne cropping system, resulted in a higher nutrient energy ratio (25.6), as legume crops are nitrogen fixers. More labor engagement with Bajra–Napier hybrid + legume (cowpea, sesbania and lucerne) cropping systems resulted in higher human energy profitability (174–191.8). It was observed that fertilizers (as an inorganic nutrient source), FYM (as an organic nutrient source) and diesel (as a fuel) presented as major carbon as well as energy input components/sources in the cultivation of different fodder cropping systems in the current study. Overall, the adoption of Bajra–Napier hybrid + legume (lucerne and cowpea) cropping systems will help to reduce the carbon footprint and maximize the energy use efficiency of systems while sustaining livestock production through higher productivity under the present scenario of climate change and limited resource availability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12081783/s1, Table S1: Quantity of manure and chemical fertilizers applied to each cropping systems.

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