

Energy use Pattern and Carbon Footprint in Onion Production: Implications for Sustainable Agriculture and Renewable Energy Policy

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Abstract:

Agriculture contributes a significant portion in total greenhouse gas (GHG) emission in the world in which India is contributing around 7%. Implementation of new policies aimed at reducing the greenhouse gas emissions from agricultural sector is now a major concern in the world. To implement the Sustainable Development Goals (SDGs) 7.0 of United Nations in agriculture and allied sectors, it has become necessary to generate policies regarding implementation of modern renewable energy sources as a substitute of conventional sources. In this context, a study was conducted to determine the amount of energy used in vegetable production in Karnataka state of India based on real time data collected during the agricultural year 2021-23. Data was collected using a modified stratified two stage random sampling scheme. Data on details of basic energy inputs and outputs were collected, and survey weighted estimates were generated. Parametric Data Envelopment Analysis (DEA) using stochastic frontier analysis was applied to distinguish between the efficient and non-efficient farm households in the study area. Furthermore, the estimates of amount of Carbon-Dioxide (CO₂) produced from each process involved during the production of a crop emphasizes the urgent need for the formulation of policies aimed at sensitization farm households towards efficient use of natural resources to mitigate the problem of global warming.

Keywords: Estimates of CO₂ emissions; Vegetable production; Renewable energy; Data envelopment analysis.

1. Introduction

Global warming poses major challenges to sustainable agriculture. Rising temperatures and erratic weather patterns threaten crop productivity and long-term sustainability worldwide. In agriculture, energy use during crop management significantly contributes to greenhouse gas (GHG) emissions through farm practices, fossil fuel-powered machinery, transportation, and processing. Pathak et al. (1) report that agriculture accounts for about 11% of global GHG emissions, with Indian agriculture contributing roughly 7% of the global agricultural share. Post-Green Revolution (1970–2010), GHG emissions from Indian agriculture rose by approximately 75%. Sustainable agriculture and energy management are essential for mitigating climate change, cutting emissions, and securing food supplies. Key strategies include adopting renewable energy, energy-efficient practices, carbon sequestration, and sustainable transportation. Resilient farming systems that promote biodiversity, conserve resources, and minimize emissions can effectively address global warming. For assessing energy efficiency at the farm or household level, Data Envelopment Analysis (DEA) offers a

robust framework to evaluate performance and pinpoint improvement areas. DEA involves defining inputs and outputs, normalizing data, identifying top-performing units, calculating efficiency scores, and recommending enhancements.

As a leading onion producer, India faces concerns over inefficient input and resource use, especially under climate change pressures. India contributes around 6.6% of global CO₂ emissions, ranking third after China and the USA (2). Onion farming is energy-intensive due to labour-heavy processes like transplanting, fertilization, weeding, and harvesting (3). Quantifying energy use in practices such as land preparation, sowing, manure and fertilizer application, plant protection, irrigation, harvesting, detopping, and grading has become critical for sustainable resource use. Modern agriculture consumes more energy than traditional systems due to increased mechanization (4). Energy use in farming depends on mechanization levels, labour force, and arable land availability (5). The Green Revolution boosted productivity through high-yielding varieties, chemicals, and machinery, but also escalated energy demand and depleted fossil fuels. The WHO's 2019–2023 strategy highlights how such practices degrade environmental quality via CO₂ and GHG emissions (6). Achieving UN SDG 7 requires transitioning to renewable energy sources (7). Despite India's global influence, many processes, particularly in rural areas where agriculture dominates livelihoods, rely on conventional energy. An IRENA report (8) notes that 834 million of India's 1,190 million population lived rurally in 2017 (9), with 700–800 million depending primarily on traditional energy (10). Robust energy statistics are vital for shaping renewable energy policies (11). Pathak et al. (1) advocate for methodologies to quantify agricultural GHG emissions and mitigation strategies tailored to India. With cheap energy no longer viable (12), enhancing farm household energy efficiency is key to sustainable production (13). Optimizing conventional inputs (fuel, pesticides, fertilizers, weed control) via practices like conservation agriculture and zero tillage can boost profitability while preserving the environment.

IRENA (9) highlights that traditional fuel use in India often goes unrecorded in official statistics. Systematic energy input surveys are needed to inform policies for sustainable agriculture, revealing environmental impacts of crop production technologies and practices. Energy input estimates across a crop season highlight opportunities for savings through better practices, improving energy ratios. This study estimates energy use efficiency among onion farm households in Karnataka, India, identifying high-energy practices and proposing policy recommendations for renewable energy adoption in rural areas.

2. Material & Methods

Survey Design and Sample Size:

The study was conducted during the year 2022-23 in the state of Karnataka, India. The study was conducted as a part of All India Coordinated Research Project (AICRP) on Agriculture and Agro-based Industries of the Indian Council of Agricultural Research, Govt. of India. For the study a sampling design and sample size was proposed by Chandra et al. (14) implemented under the project throughout India for various crops. The data on onion crop was collected from Karnataka state of India. The state has ten agro-climatic zones, namely North Eastern Transition Zone, North Eastern Dry Zone, Northern Dry Zone, Central Dry Zone, Eastern Dry Zone, Southern Dry Zone, Southern Transition Zone, Northern Transition Zone, Hilly Zone and Coastal Zone, based on rainfall pattern, quantum, and distribution; soil types, texture, depth, and physio-chemical properties; elevation and topography; and major crops and vegetation (Govt of Karnataka [15]). The majorly grown vegetable crops of the state are onion, potato, tomato, chillies etc.

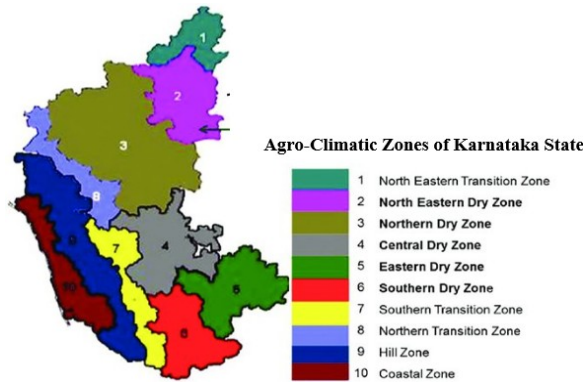


Fig1: Agro-Climatic Zones of Karnataka (Source: Govt of Karnataka, India)

Five of the ten agro-climatic zones (ACZs) in the state are having significant area under onion crop, and all these zones were considered under the study. A stratified two-stage random sampling design as proposed by Chandra et al. (14) was adopted for the selection of ultimate stage units i.e. farm households in the rural villages. First a list of eligible farm households growing the target crop was prepared. Hamlet groups were created for selection of eligible farm households. In the sampling design, the agro-climatic zones were considered as strata. The villages within the strata (ACZs) were considered as the first stage unit (FSU) and the farm households within the villages were considered as the second stage unit (SSU) of selection. Based on the resource availability and other aspects, a sample of 30 villages were allocated to five strata (ACZs) in proportion to the area of cultivation under the onion crop as:

$$\text{Number of villages to be selected from } i\text{th ACZ} = \frac{\text{Area of the onion crop in the } i\text{-th ACZ}}{\text{Area of the onion crop in all selected ACZ}} \times 30$$

Further, from each of the selected village, 20 eligible farm households were selected randomly. First, a frame of the eligible farm households was formulated based on the available land records of the village. From the sampling frame, 20 eligible farms/farm households were selected using equal probability without replacement sampling design. Thus, a total of 600 farm households were selected for energy auditing in the onion crop of the Karnataka state.

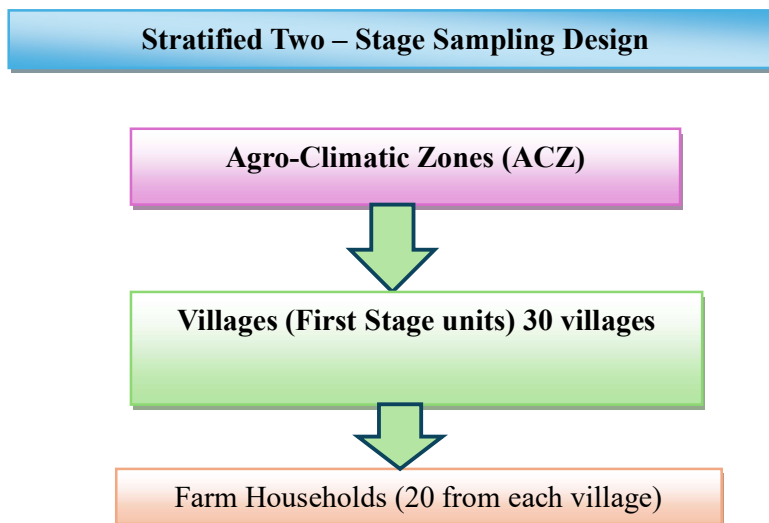


Fig 2: Flowchart of selection of farm households through Stratified Two-stage Sampling

Data Collection:

Data were collected by using three questionnaires as:

Questionnaire-I: Listing/Enumeration of Selected Villages: In this questionnaire, the eligible farm households of the selected villages were listed. The primary data was collected on

- (i) Basic information about the selected village, and
- (ii) Farm Household wise information.

Questionnaire-II: List of operational holdings in selected village (Re-tabulation from Questionnaire-I)

Questionnaire-III: Detailed operational holding survey: In this questionnaire, information on basic energy inputs and outputs, detailed energy consumption was collected and verified with measurements for both source and operations wise i.e. energy use in land development, land preparation, seed bed preparation, planting, irrigation, weeding, fertilizer application, chemical application, harvesting etc.

Estimation Procedure and Data Analysis

Estimates of energy consumption for various farm operations based on collected field data were calculated following Chandra et al. (14) and Aditya et al. (16). This study aims to generate the design based consistent survey weighted robust estimates of inputs in crop production. Besides, estimates of different parameters, Percentage Coefficient of Variation (%CV) of the estimates have also been calculated using the above given formula. Estimates were generated at two different levels i.e. at the ACZ level and at the state level following the design-based survey estimation technique using stratified multistage random sampling design. Further, information was available on categorization of the farm households based on their total area under cultivation. There are three categories small, medium and large based on their holding sizes less than 1ha, in between 1 to 2 ha and more than 2 ha respectively. The production of the energy estimates at the ACZ level was also done based on these farm household categories to infer about the energy use patterns at various levels of disaggregation within the selected sample size.

Energy equivalents:

Energy inputs in the form of human labour, use of machinery, diesel, fertilizer, electricity etc. and these inputs have different energy equivalents. Main energy inputs used in onion production are presented in Table 1 (16).

Table 1. Energy equivalent of inputs and output in agricultural production

Input	Energy equivalent (MJ/unit)
Inputs	
Human Labour	
Man (Man-hour)	1.96
Women (Woman-hour)	1.57
Machinery (in hour)	64.80
Diesel oil (in litre)	56.26
Electricity (in kWh)	11.68

Farmyard Manure (kg)	0.30
Weedicides (kg)	120.00
Seeds (kg)	1.60
Output	
Onion (kg)	0.80

Based on the energy equivalents of the inputs and output (Table 1), the total input and output energy for production of onion crop was calculated and then using the data on input and output energy, the survey estimates were produced at different levels of disaggregation for each input and output processes involved in the production of the onion crop.

Data Envelopment Analysis (DEA):

The DEA is an analysis method to measure the relative efficiency of a set of comparable units called decision-making units (DMUs) by using some specific mathematical programming models [17]. In agriculture, farm households have more control over inputs rather than output levels, therefore input-oriented DEA models are more appropriate in this study to reduce inputs consumed in the production. In 1978, Charnes et al. [18] developed Charnes-Cooper-Rhodes (CCR) model, which exhibits constant returns to scale (CRS). The CCR model, also known as the Data Envelopment Analysis (DEA) model, is a linear programming technique used to evaluate the relative efficiency of decision-making units (DMUs) that use multiple inputs to produce multiple outputs.

Stochastic Frontier Analysis (SFA), developed by Aigner et al. (19), represents a parametric approach to measuring technical efficiency by estimating a stochastic production frontier that separates inefficiency from random noise. Unlike Data Envelopment Analysis (DEA), which assumes a deterministic frontier, SFA posits that observed output deviations from the maximum potential arise from two components: a symmetric random error term capturing exogenous shocks, measurement errors, and weather effects, and a one-sided inefficiency term typically half-normal or exponential.

Calculation of GHG Equivalent

For calculation of GHG equivalent (kg CO₂eq per/acre) the average survey-based estimates of the inputs (MJ/acre) were multiplied with the Green House Gas (GHG) coefficients (kg CO₂eq / MJ). The GHG Coefficients were given in the following table 2.

Inputs	GHG Coefficient (kg CO₂eq /MJ)
Human labour (hr)	0.700
Machinery (MJ)	3.320
Electricity (kW/h)	0.820
FYM (kg)	0.006
Nitrogen (kg)	1.300
Phosphorus (kg)	0.200
Potassium (kg)	0.200
Weedicide (kg)	6.300

Diesel (l)	0.940
Seed (kg)	7.630

Table 2. Input wise GHG Coefficients (Aditya et al., 2025)

3. Results and Discussion

Energy Use Pattern:

The data were collected from 600 households on energy use pattern in onion crop production in Karnataka state of India during 2021-23 using personal interviews. The operation wise consumption of energy input is presented in Fig 5 and the estimates of average energy consumption for all operations along with coefficient of variation are presented in Table 3. In this study, survey weighted design-based estimates were produced because design-based estimation in sample surveys is generally considered to be robust to estimate the deviations from assumptions. The estimators can produce reliable estimates even when the population distribution is unknown or complex.

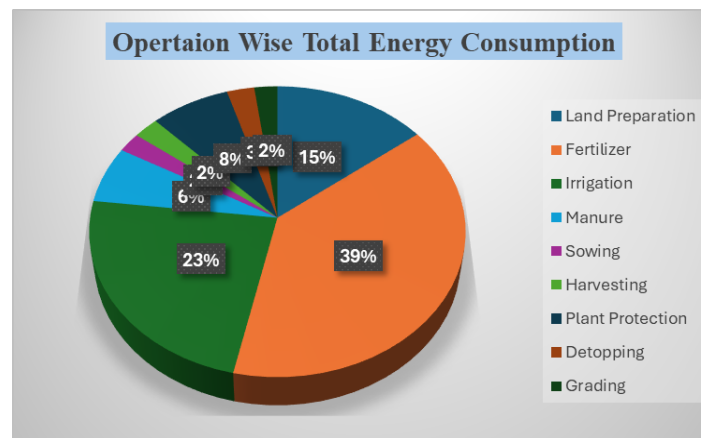


Fig 3: Operation wise Consumption of Energy Input in Onion

Operation	Estimate of Average energy Input (MJ/acre)	Coefficient of Variation (%)
Land Preparation	3384.95	12.06
Fertilizer	9086.63	4.09
Irrigation	5471.43	1.26
Manure	1469.73	17.40
Sowing	508.84	8.65
Harvesting	561.05	3.16
Plant Protection	1746.83	9.15
Detopping	603.79	3.44
Grading	506.75	2.71

Table 3: Operation-wise estimates of average energy input in onion production in Karnataka, India

Onions are generally transplanted to the main field, which is properly ploughed to eliminate agricultural remains and soil clods by using double plough, Tyne cultivator and rotavator. The energy consumed in case of land preparation for main field was 3384.95 MJ/acre, which

was 15% of total input energy used in onion production. After transplanting fertilizer application, weed management and irrigation are some of the operations which are required for efficient production of the crop. The onion is more susceptible to weed competition than other crops, mainly due to its slow growth during the early stages of development and inherent characteristics such as short stature, non-branching, and shallow root system. The energy input in terms of fertilizer application in onion had a significant share of 39% followed by irrigation (23%), land preparation for main field (15%) and plant protection (8%). There was a significant decrease in energy consumption in the onion crop for fertilizer application and land preparation as compared to the results shown in Aditya et al. (16) based on the data collected during 2021-22, the first year of collection of data. It is recommended that energy input in terms of fertilizers can be saved by using liquid fertilizer, precision application of fertilizers and spreading the awareness among farm households for optimal application of fertilizer.

From the above table, the energy consumption for plant protection was 1716.77 MJ/acre, which was 8% of total energy input. Energy input in terms of irrigation in onion crop production was 3010.86, which were 23% of total energy input and there was a significant increase in both these activities as compared to Aditya et al. (16). Onion crop requires a consistent supply of water throughout its growth cycle. Irrigation ensures that the plants receive the necessary amount of water to grow and develop properly. Irrigation helps to maintain uniform soil moisture levels, which promotes uniform growth of onion plants. Irrigation requirement in onions mostly depends upon the season, soil type and irrigation method. The other processes involved has minimalistic share which have almost constant share as compared to last year.

Agroclimatic zone wise estimates of average energy (MJ/acre) consumption for onion production in Karnataka was given in Table 4 and Agroclimatic zone vs holding size wise estimates of average energy (MJ/acre) consumption for onion production in Karnataka for each operation is presented in Table 5.

Agroclimatic Zones	Land preparation	Fertilizer	Irrigation	Manure	Sowing	Harvesting	Plant protection	Detopping	Grading
Central Dry Zone	3584.86	8867.68	4666.78	680.44	405.25	614.77	1326.71	575.49	507.35
Northern Dry Zone	3726.73	7940.24	5155.67	1678.99	519.72	659.85	3273.42	695.15	592.25
Northern Transition Zone	1961.51	6577.45	5675.85	778.83	279.93	542.67	1183.10	528.71	456.43
Southern Dry Zone	5664.71	9909.96	5827.43	2513.46	2063.60	626.67	1618.10	667.76	523.44
Southern Transition Zone	4331.95	13894.23	5880.05	2355.65	486.53	427.35	1014.20	602.34	473.77

Table 4. Operation wise estimates of average energy (MJ/acre) consumption for onion production under different Agroclimatic Zones of Karnataka

Agroclimatic Zones	Holding Sizes	Land preparation	Fertilizer	Irrigation	Manure	Sowing	Harvesting	Plant protection	Detoppin g	Gradin g
Central Dry Zone	Small	3841.27	8845.42	4721.57	751.44	409.72	609.38	1278.36	549.19	510.14
	Medium	3856.11	8877.96	4612.24	589.68	377.46	628.22	1356.92	602.07	529.26
	Large	3320.54	8872.58	4670.30	695.71	417.99	610.12	1333.16	573.59	494.35
Northern Dry Zone	Small	4225.59	7423.71	5177.63	1910.85	558.90	688.70	3922.20	725.05	636.26
	Medium	3721.03	8079.83	5105.23	1766.25	517.18	649.07	3162.35	698.97	598.35
	Large	3552.74	8047.53	5175.36	1549.12	507.20	655.49	3103.64	682.45	573.31
Northern Transition Zone	Small	2030.27	6063.99	5610.45	788.97	379.53	563.59	944.35	523.44	457.95
	Medium	2104.58	6559.69	5916.19	829.81	320.24	521.39	1138.08	509.43	428.37
	Large	1877.27	6663.65	5561.49	750.97	244.16	550.53	1242.17	539.47	470.70
Southern Dry Zone	Small	5455.43	9909.89	5879.72	2327.63	2097.85	703.19	1603.55	707.61	523.44
	Medium	5495.34	9875.04	5963.72	2624.61	2065.54	617.36	1708.98	674.44	523.44
	Large	5996.35	9959.89	5610.34	2434.32	2046.15	607.17	1494.51	641.13	523.44
Southern Transition Zone	Small	5490.37	13037.80	5880.05	2323.78	600.93	310.23	1011.82	552.49	426.42
	Medium	4642.90	13412.96	5880.05	2963.99	528.30	417.62	1022.55	612.76	468.51
	Large	4131.91	14167.80	5880.05	2052.70	461.24	436.71	1010.12	599.05	478.23

Table 5. Operation and Holding Size wise estimates of average energy (MJ/acre) consumption for onion production under different Agroclimatic Zones of Karnataka

From Table 4 and 5, it can be clearly seen that, Fertilizer application, irrigation and land preparation contributes to maximum energy consumption among all other applications in all the ACZs and within all holding sizes of farm households i.e. small, medium and large. From Table 5, it can also be seen that the medium to large farmers are the ones which are using the maximum amount of non-renewable energies for production of crops and the fact is obvious as they have more access to the non-renewable sources of energies than the small and marginal farmers. Among all the zones, southern transition zone was the one which used the maximum amount of energy among all other zones and is considered the least efficient zone in accordance with energy use. There is urgent need for sensitization of the farms for use of renewable energy sources instead of the traditional energy sources to reduce the production of the greenhouse gas emission which is causing a significant role in global warming and climate change.

Estimation of Greenhouse Gas Emission:

For estimation of greenhouse gas emissions, first the average energy estimates in MJ/acre were found out following the stratified two stage sampling design and then it was multiplied by the GHC equivalent (kg CO₂eq per/acre) given in Table 2.

Process	Energy Estimates (MJ/acre)	%CV	CO ₂ equivalent (kg CO ₂ eq per/acre)	CO ₂ Produced (kg/Acre)
Mechanical	246.10	3.67	3.32	817.05
Manual Labour	3101.31	3.02	0.70	2170.92
Diesel/petrol	3853.08	12.82	0.94	3621.89
Electricity	2802.12	28.36	0.82	2297.74
FYM	1269.23	21.14	0.01	7.62
Fertilizer	9118.27	4.38	1.70	15501.06
Seed	12.24	4.34	7.63	93.36
			Total	24509.64

Table 6. Average CO₂ Produced by the production Processes of Onion

From the above Table 6, use of fertilizer and natural resources like diesel/petrol, electricity and manual labour have produced the maximum amount of CO₂ among all other processes

involved in production of onion crop from field preparation to harvesting for the state of Karnataka, India with total of 24509.64 kgs of CO₂ produced by the entire process. There is an immediate need for upgrading the process of cultivation with alternatives emitting less CO₂ than the existing processes.

3.1 Data Envelopment Analysis (DEA):

Data envelopment analysis was performed with the aim to distinguish between efficient and non-efficient farm households with respect to energy inputs in the onion production. The results have been presented in Fig 4. 208 out of 600 farm households had technical efficiency score of 0.95 to 1 and out of these technically efficient farm households, 194 farm households had a pure technical efficiency score of 0.95-1.00 indicating that they are efficiently using the energy inputs as compared to other farm households in the study area.

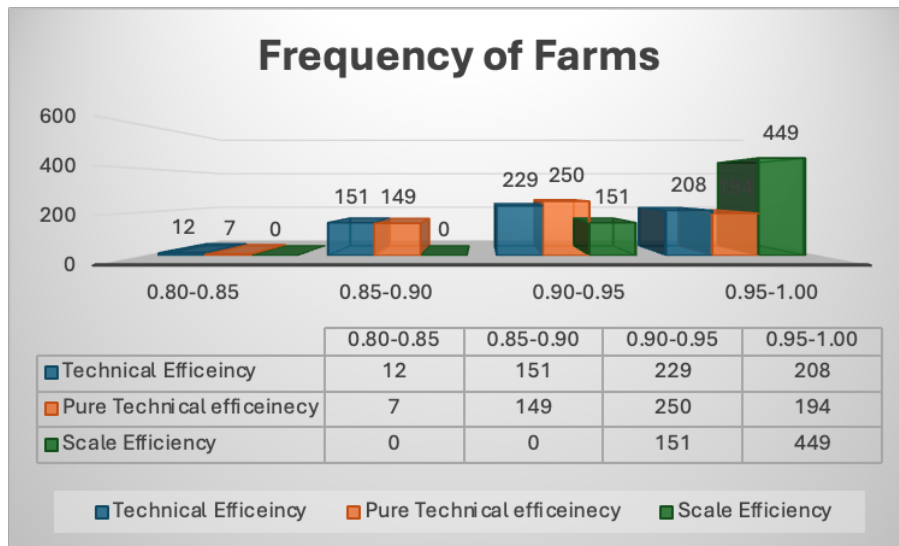


Fig 4: Efficiency score distribution of onion farm households

Metric	Mean	SD	Min	Median	75%	Max
Technical Efficiency	0.927	0.050	0.779	0.934	0.970	1.000
Pure Technical Eff.	0.931	0.046	0.794	0.937	0.969	1.000
Scale Efficiency	0.961	0.033	0.910	0.994	1.017	1.098

Table 7: Technical Efficiency (CRS), Pure Technical Efficiency (VRS) and Scale Efficiency of onion farm household in the Karnataka state of India

Table 7 provides an overview of the average values for technical efficiency, pure technical efficiency, and scale efficiency. The average technical efficiency gives details on potential resource savings that might be achieved while keeping the same level of output. Technical efficiency, pure technical efficiency, and scale efficiency were found to have average values of 0.927, 0.931, and 0.996, respectively, for all 600 farm households. The average technical efficiency for inefficient farm households was 0.927. This suggested that the same level of output could be produced with 92.7 % of the resources if these units were performing properly and 7.3% of total resources might be saved. This implies that there is considerable scope in improvement of inefficient farm households to enhance their energy use efficiency which will directly impact on their profitability and sustainability through agriculture. The

average scale efficiency was 0.961, which indicated that without changing technology of farm management, some energy could be saved from various sources if inefficient farm households use their resources effectively. A farm household with a technical efficiency less than one is using more energy than is required from the various sources. These results, suggest that there is need for sensitization of the inefficient farm households towards efficient use of inputs during crop production to help in achieving sustainability in agricultural production.

Conclusions

The study reveals substantial energy consumption in onion production across India, with fertilizer application leading, followed by irrigation and land preparation. Non-renewable inputs like fertilizers and petrol for mechanization dominate usage, signalling heavy reliance on fossil fuels that could trigger long-term environmental issues such as global warming, nutrient overload, and groundwater contamination. This pattern extends nationwide, highlighting vast potential for energy savings and adoption of renewables like solar or wind power. Such shifts would curb global warming and address rising greenhouse gas emissions from crop management in rural India, where farming remains the primary livelihood. Raising awareness among farm households about excessive CO₂ impacts is essential. Promoting conservation agriculture, integrated nutrient management, and biological controls can cut chemical energy inputs while safeguarding human health and ecosystems. Additionally, bio-fertilizers, biocontrol agents, biodiesel, and solar-powered equipment should be prioritized. Deploying high-yielding varieties would further slash chemical and irrigation needs, boosting energy use efficiency and productivity for onion cultivation.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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