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ENERGY AUDITING AND CROP PRODUCTIVITY: A CASE STUDY ON RESOURCE USE EFFICIENCY IN AGRICULTURE

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ABSTRACT

Energy auditing in agricultural practices from land preparation to harvesting is essential for optimizing energy use, reducing costs, and improving sustainability. This study evaluates both direct energy inputs like fuel, electricity, human labor and indirect energy inputs like fertilizers, pesticides, seeds, and machinery at different stages of crop production. The process includes analyzing energy consumption during land preparation, sowing, irrigation, fertilizer application, pest control, harvesting, and post-harvest handling. The performance indicators such as energy use efficiency, energy productivity, and net energy balance are used to assess sustainability. This study focuses on the energy auditing of agricultural practices (Kharif Season-2024) in Agrahara Nattamangalam Village, Namakkal. To enhance efficiency, adopting conservation tillage, precision farming, renewable energy sources (solar irrigation, biogas), and energy- efficient machinery was proposed. The energy auditing provides valuable insights for improving agricultural sustainability by reducing reliance on non-renewable energy, minimizing environmental impact, and ensuring long-term productivity.
***Keywords* :** Audit, Energy management, Energy utilization, Net energy, Energy output.

Introduction

Agriculture is the science and practice of cultivating plants and raising animals for food, fibre, medicine, and other essential products. It has been a fundamental part of human civilization for thousands of years, enabling societies to transition from nomadic lifestyles to settled communities. Agriculture supports economies by providing employment, raw materials for industries, and a stable food supply. Over time, technological advancements such as irrigation, mechanization, and biotechnology have significantly increased productivity. However, modern agriculture also faces challenges like climate change, soil degradation, and the need for sustainable farming practices. As a result, efforts are being made to balance agricultural productivity with environmental conservation to ensure food security for future generations. Agricultural practices refer to the various methods and techniques used in farming to cultivate crops and rear livestock efficiently. These practices have evolved over time, incorporating both traditional and modern approaches to improve productivity, sustainability, and food security. Factors such as climate, soil conditions, technology, and available resources influence the choice of agricultural methods. Sustainable farming, organic farming, mechanized agriculture, and precision farming are some of the widely used techniques today. By adopting efficient agricultural practices, farmers can enhance yields, conserve natural resources, and reduce environmental impact while ensuring a stable food supply for growing populations.

Energy Auditing

Energy auditing in agriculture is a systematic process of analyzing energy consumption within farming operations to identify inefficiencies and suggest improvements. As agriculture relies heavily on various forms of energy such as electricity, fuel, and human labour conducting an energy audit helps optimize energy use, reduce costs, and minimize environmental impact. With the increasing demand for sustainable farming, energy audits play a crucial role in enhancing efficiency in operations like irrigation, greenhouse management, crop production, and livestock farming. By assessing energy inputs and outputs, farmers can adopt energy-saving technologies, switch to renewable energy sources, and implement better management strategies. Energy auditing in agriculture helps identify problems that lead to high energy consumption and inefficiency. One major issue is the excessive use of electricity and fuel in farming activities such as irrigation, greenhouse operations, and machinery use. Many farms rely on old and inefficient equipment like tractors and pumps, which consume more energy than modern, energy-saving alternatives. Poor maintenance of machines also increases energy waste, as worn-out equipment requires more power to function properly. Irrigation systems often have leaks or outdated pumps, leading to unnecessary water and energy use. Another problem is the overuse of fertilizers and pesticides, which require a lot conventional energy sources instead of using renewable options like solar, wind, or biogas, which could help cut costs and reduce environmental impact. Poor workflow management, such as improper planning of field activities, can also lead to unnecessary fuel and electricity consumption. By identifying these problems, energy audits help farmers find better ways to save energy, reduce costs, and improve sustainability in agricultural operations.

Efficient energy use in agriculture has become increasingly important for ensuring sustainability and optimizing production. Several researchers have explored energy auditing and efficiency across different cropping systems, focusing on tillage methods, residue management, fertilizer usage, weed control, and farm operations. An energy-use audit and optimization study in the rice-wheat system was conducted under five tillage regimes zero tillage with residue retention (ZTR), conventional tillage with residue incorporation (CTR), minimum tillage with biochar (MTB), conventional tillage with biochar (CTB), and conventional tillage alone (CT)combined with varying nitrogen fertilizer levels using biochar-coated urea. Using Data Envelopment Analysis (DEA) through CCR and BCC models across 30 decision-making units, it was found that ZTR with 125% recommended nitrogen resulted in the highest grain yield energy (206,939.3 MJ/ha), while MTB was the most energy-efficient, reducing input energy by 13.7–52.1% compared to others. Key energy savings were recorded in irrigation, fertilizers, fuel, and electricity. Notably, 70% of the decision-making units were energy inefficient, suggesting that optimized tillage, residue, and nitrogen management could conserve up to 20,795 ± 5557 MJ/ha (12.76%) input energy (Tony Manoj Kumar Nandipamu *et al.*, 2025). A study of global energy-use patterns in 49 major crops across Asia and Africa classified energy inputs as direct (manual labor, animal power, fuel) and indirect (fertilizers, machinery, pesticides, seeds). The findings highlighted excessive use of fertilizers and pesticides in several countries and emphasized the need for monitoring energy efficiency across crop operations like tillage, irrigation, sowing, and harvesting (Raveena Kargwal *et al.*, 2022). The importance of energy auditing in crop production was emphasized under the Energy Conservation Act, 2001. The study explained that energy audits involve monitoring, verification, and analysis of energy use to make recommendations for efficiency improvements. Energy was categorized into direct and indirect, as well as commercial, non-commercial, renewable, and non-renewable sources. It stressed the necessity of operation-wise energy assessment in the face of declining labor availability (Swaminathan *et al.*, 2020). The energy estimation of machinery use during potato planting was examined using the comb and smooth planting methods. The research provided a basis for calculating energy equivalence in mechanized field operations (Stroyanovsky *et al.*, 2015).

Energy inputs in cassava production were evaluated across 10 farms, showing that 78.67% of energy use was indirect, with fertilizers (64%) and diesel (19.5%) as the major contributors. The study reported net energy and productivity at 46,655.77 MJ/ha and 1.18 MJ/kg, respectively. Mathematical expressions were applied to estimate energy use in operations such as land preparation, planting, maintenance, and harvesting (Isaac Bamgboye *et al.*, 2015). Rice cultivation across different landforms wetland, terrace wetland, upland, and jhum land was studied in Arunachal Pradesh. Labor and seed requirements varied across landforms, with machine energy highest in terrace wetland systems. Despite higher input costs, wetland rice cultivation yielded better net returns and B:C ratios. Jhum land, though traditionally managed and agrochemical-free, recorded the highest energy productivity and output-input ratio (Suresh Kumar *et al*., 2013). An analysis of energy requirements for various weed management strategies in wheat including manual, chemical, and criss-cross sowing methods revealed energy inputs ranging between 19,589 and 20,472 MJ/ha. Fertilizers accounted for about 50%, machinery for 20%, and irrigation for 17% of total energy use. Weed management contributed up to 4.22% of input energy (Chaudhary *et al*., 2012). Winter tomato production under greenhouse conditions in Turkey was examined, identifying fertilizers, electricity, manure, and diesel as major energy inputs. With an energy input of 61,434.5 MJ/ha and a yield of 57,905.1 kg/ha, the output-input ratio stood at 0.8. The study highlighted the inefficient use of chemicals and recommended optimizing indirect energy inputs (Burhan Ozkan *et al*., 2011). A decade-long comparative study of energy efficiency between organic farming and integrated farming using full (100%) and reduced (50%) pesticide inputs demonstrated that organic systems produced better net energy outputs and efficiency. This was attributed to reduced agrochemical inputs, showcasing the benefits of low-input sustainable farming (S. Deike *et al*., 2008). Energy audits of six cropping systems, including rice-wheat, maize-wheat, and rice-mustard-green gram, revealed fertilizers as the highest energy-consuming input (32.6–41.7%), followed by irrigation and machinery. While the rice-wheat system recorded the highest net energy return (102,865 MJ/ha), the rice-mustard-green gram system yielded superior economic returns, illustrating the influence of cropping system design on energy and monetary efficiency (Chaudhary *et al*., 2006).

Materials and Methods

Energy auditing in agriculture helps identify issues that lead to excessive energy consumption and inefficiency, such as the overuse of electricity and fuel in irrigation, greenhouse operations, and outdated machinery like tractors and pumps. The energy audit process begins with pre-auditing preparations, which involve selecting the target area in this case, Agrahara Nattamangalam village in Namakkal district and defining the scope and objectives of the audit.

Agrahara Nattamangalam is a village located in the Lakkapuram Panchayat of Namakkal district, Tamil Nadu, falling under the Puduchatram block. The village spans a total geographical area of 131 hectares and 5.5 ares. Of this, 89 hectares and 22.5 ares constitute agricultural land, with 62 hectares and 50 ares currently under cultivation, while the remaining 26 hectares and 72.5 ares are classified as culturable wasteland. Additionally, 42 hectares and 28 ares of the land area comprise the village lake. Geographically, the village is situated at a latitude of 11.3°N and longitude of 78.2°E, with an elevation ranging from 200 to 300 meters above sea level. The region falls within the semi-arid zone of Tamil Nadu, characterized by red loamy and black cotton soils that are highly suitable for agriculture. The area does not benefit from delta irrigation due to the absence of rivers or streams, relying instead on groundwater sourced from borewells and open wells for both irrigation and drinking purposes. Major crops cultivated in the area include maize, cassava, cotton, groundnut, sorghum, pulses, and sesame. This village was selected for energy auditing due to its year-round agricultural activities. In addition to seasonal crop cultivation, perennial crops such as coconut are grown, and many farmers also engage in poultry and livestock farming including cows, buffaloes, sheep, and goats to supplement their income.

Literature collection plays a key role by providing energy equivalence values for various agricultural inputs and outputs, along with standardized procedures for auditing. A field survey follows, involving direct inspections and interactions with farmers to understand their practices. During data collection, comprehensive information is gathered on farm profiles, energy-consuming activities such as machinery usage, irrigation methods, labor, fertilizers, and pesticides, as well as energy outputs like crop yield and residues. The data is then analyzed using statistical techniques and energy conversion to megajoules, helping evaluate energy efficiency indicators. A structured data sheet is prepared to record and compare inputs and outputs systematically across farms and cropping systems.

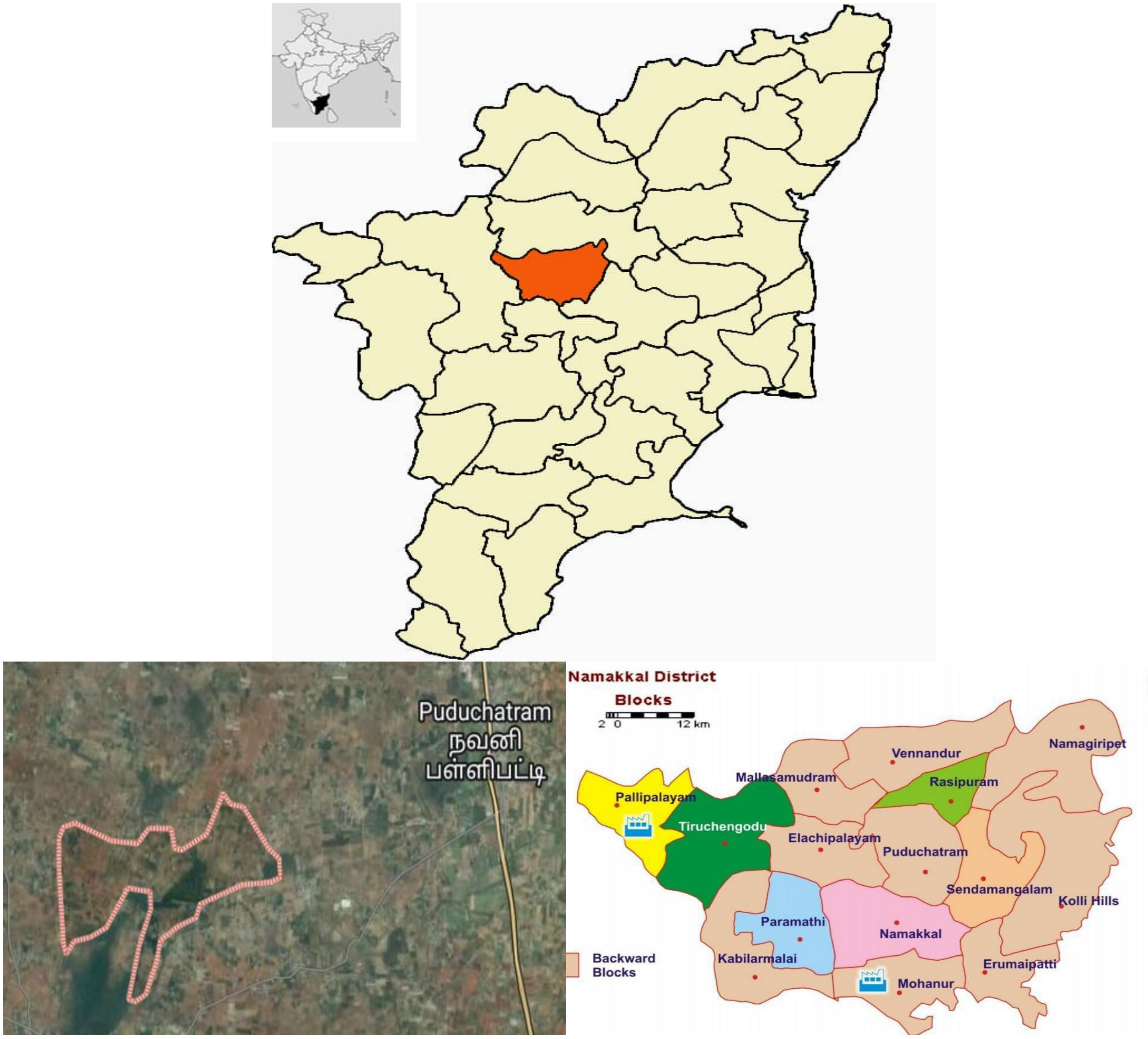

Fig. 1 : Namakkal - Blocks

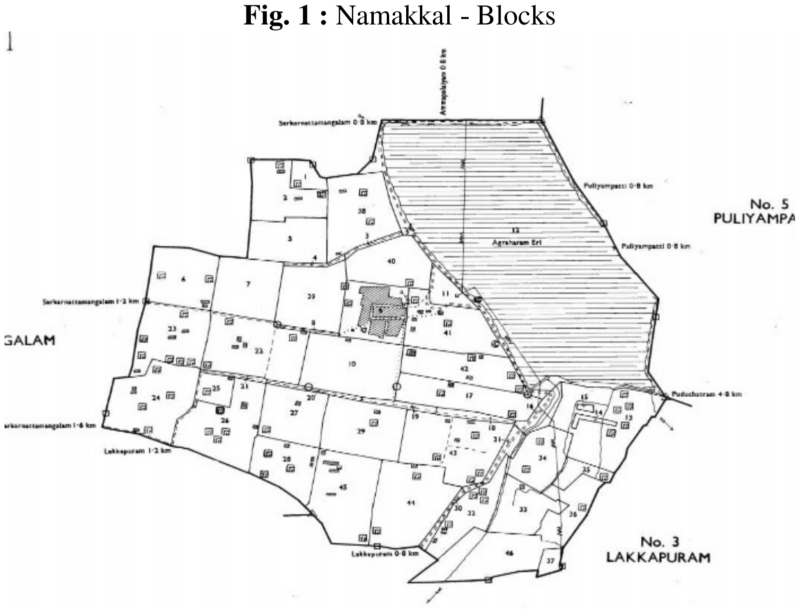

Fig. 2 : Agrahara Nattamangalam Map

Table 1: Energy Equivalents of Various Inputs Used in Agricultural Operations

Energy Source	Unit	Energy Equivalent (MJ/unit)
1. Human Labour		
a. Man	hour	1.96
b. Woman	hour	1.57
c. Child	hour	0.80
2. Fuel		
a. Diesel	litre	56.31
b. Petrol	litre	48.23
3. Fertilizer		
a. Nitrogen (N)	kg	60.60
b. Phosphorus (P_2O_5)	kg	11.10
c. Potash (K_2O)	kg	6.70
4. FYM (Farmyard Manure)	kg	0.30
5. Electricity	kWh	11.93
6. Irrigation Water	hour	1.02
7. Seed	kg	14.70
8. Machinery Use		
a. Tractor	hour	10.95
b. Implement	hour	62.70
9. Chemicals		
a. Herbicide	kg	238.00
b. Pesticide	kg	100.00
10. knapsack sprayer	hour	**0.17**

The Table 1 presents the standard energy equivalents of various agricultural inputs commonly utilized in field operations. These values, expressed in megajoules (MJ) per unit, serve as conversion factors to calculate the total energy input (MJ/ha) for different farming activities. The conversion enables a quantitative assessment of energy consumption across crops, practices, and regions.

Table 2 : Energy Equivalent Values of Agricultural Output (MJ/kg Dry Weight)

Category	Energy Equivalent (MJ/kg)	Remarks
Cereals	14.7	Grain (e.g., wheat, maize, rice)
Pulses	14.7	Grain (e.g., moong, lentil, soybean)
Oilseeds	25.0	Seed (e.g., groundnut, mustard)
Fibre Crops	11.8	Fibre (e.g., cotton, jute, sun hemp)
Straw	12.5	Used for feed and other farm activities
Stalks, Cobs & Fuelwood	18.0	Used as feed, fuel, compost, etc.
Leaves & Straw from Leaves	10.0	Multi-purpose utility
Cotton Seed	25.0	Used for oil extraction and other purposes
Fibre Crop Seed (non-cotton)	10.0	Fuel crop seed or other general utility

Evaluation Parameters

The total energy input for various agricultural activities was calculated using the following components:

a) Manual Energy Input

Manual or human energy (E_m) was calculated based on the number of labourers and the time they spent on specific farm operations. The formula used is:

$$E_m = 1.96 \times N_m \times T_m \text{ (MJ)}$$

Where:

- N_m = Number of labourers involved in the operation
- T_m = Effective working hours per labourer (in hours)
- 1.96 MJ = Energy equivalent per man-hour

Only direct labor hours were considered, while other influencing factors (such as age, skill, or physical condition) were not accounted for.

b) Mechanical Energy Input

Mechanical energy was estimated by measuring the diesel fuel consumption during various operations like tillage, sowing, threshing, winnowing, and irrigation. The energy from diesel use was calculated using the formula:

$$E_f = 56.31 \times D \text{ (MJ)}$$

Where:

- 56.31 MJ/L = Energy equivalent of diesel
- D = Diesel consumed in liters

This includes diesel used in tractors and irrigation pumps.

c) Other Input Energies

Energy from additional inputs including seeds, fertilizers, chemicals, and organic manures was estimated using standard energy equivalents. These were included in the calculation based on: type of input (e.g., fertilizers, plant protection chemicals), quantity used and associated field operations and time taken.

All agricultural operations were analyzed, including: Land preparation (plowing, puddling, etc.), Nursery raising and transplanting, Seed sowing/drilling, Intercultural operations (weeding, earthing up, etc.), Crop management (e.g., topping, detrashing), Harvesting and post-harvest handling.

Energy Input and Output Estimation

Energy inputs from all sources human labor, tractors, irrigation pumps, fertilizers, chemicals, seeds, and organic manures were measured in megajoules (MJ) using appropriate conversion factors.

Grain yield and other crop outputs over four-year average yields were also converted into energy units using standard output energy equivalents, allowing for the comprehensive assessment of energy productivity and efficiency for each cropping sequence.

Calculation of Energy Output

Output energy = Total amount of yield(kg) * energy equivalent value

i) Energy use efficiency (%) = (output energy (MJ/ha) / input energy (MJ/ha))

ii) Energy productivity (kg/MJ) = Grain yield (kg/ha) / energy input (MJ/ha)

iii) Net energy (MJ/ha) = Output energy – Input energy

Results and Discussion

Field Survey

The data extracted from the survey report, shows the land holding capacity of farmers. This data allows us to categorize farmers based on their land area, ranging from small to marginal farmers. The classification of farmers based on land holding capacity is as follows: marginal farmers own less than one-hectare, small farmers own between one and two hectares, medium farmers hold between two and ten hectares, and large farmers have more than ten hectares of land.

Total land in ha = (Total land (acre)/2.471)

= 154.45/2.471 = 62.50 ha

There are 5 marginal farmers who own less than one hectare of land, 15 small farmers with land holdings between one and two hectares, and 11 medium farmers who own between two and ten hectares of land. Interestingly, no large farmers (those with more than 10 hectares) were reported in the survey. In total, the survey covers 31 farmers, reflecting a distribution of landholding capacities that can help inform agricultural policies and support programs tailored to different types of farmers.

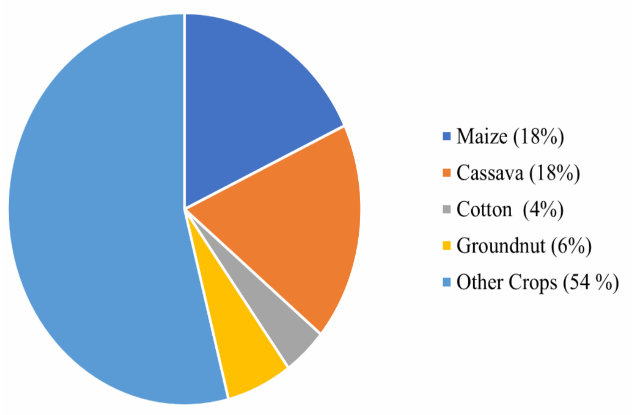

Fig. 3 : Crop distribution in Agrahara Nattamangalam Village

The land area distribution (in hectares) under various crops cultivated in Agrahara Nattamangalam village during the Kharif season of 2024. Out of a total of 62.496 hectares, Maize and Cassava each occupy 11.129 hectares, accounting for approximately 18% of the total cropped area individually. Groundnut is grown on 3.94 hectares (6.3%), while Cotton covers 2.428 hectares (3.9%). The remaining 33.87 hectares, constituting the largest share at 54.2%, is allocated to a variety of other crops, indicating crop diversification in the region. This distribution reflects the prominence of maize and cassava as major crops, while also highlighting the significant role of minor or mixed cropping systems categorized under other crops. The data serves as a foundational input for analyzing energy consumption, resource allocation, and sustainability of agricultural practices in the area.

Table 3: Energy Input (MJ/ha) from Various Sources for Different Crops during the Kharif Season in Agrahara Nattamangalam Village

Energy Source	Maize	Cotton	Cassava	Groundnut
1. Human Labour				
a. Man	261.53	213.09	707.10	92.02
b. Woman	15.52	193.97	290.96	640.11
2. Fuel				
a. Diesel	3478.55	834.85	3478.55	2087.13
b. Petrol	595.88	357.53	715.06	-
3. Fertilizer				
a. Nitrogen	1048.20	7487.13	6060.00	1515.00
b. Phosphorus	192.00	822.84	333.00	555.00
c. Potash	115.89	579.44	1206.00	502.50
4. FYM	741.30	1482.60	2965.20	1482.60
5. Electricity	8791.83	2637.55	17583.65	659.38
6. Water	1673.56	502.05	3347.11	125.51

7. Tractor Use	135.29	81.17	135.29	81.17
8. Implements	774.66	464.79	697.19	464.79
9. Chemicals				
a. Herbicide	2940.49	1470.25	4410.74	-
b. Pesticide	1482.60	741.30	2223.90	-
10. Knapsack Sprayer	4.20	2.10	6.30	-

Table 3 presents a detailed energy input analysis (in MJ/ha) for four major crops Maize, Cotton, Cassava, and Groundnut cultivated during the Kharif season of 2024 in Agrahara Nattamangalam village, Namakkal District. The table captures the energy contributions from various sources such as human labour, fuel, fertilizers, farmyard manure (FYM), electricity, water, machinery, and agro-chemicals. Notably, cassava and maize exhibited the highest total energy consumption, primarily due to extensive use of fertilizers, electricity, and irrigation water. Cotton showed a particularly high energy input from nitrogen fertilizers and female labour, reflecting its labour-intensive nature. Groundnut had comparatively lower energy input across most parameters, indicating its suitability for low-input farming systems. Diesel remained a major fuel source for all crops, while petrol usage was limited or absent in groundnut cultivation. The use of herbicides and pesticides was prominent in cassava and maize but not recorded in groundnut, possibly suggesting alternative pest management practices. This analysis underscores the variability in energy use patterns across crops and provides critical insights for optimizing energy inputs to improve sustainability and efficiency in crop production systems.

Energy utilization for maize cultivation

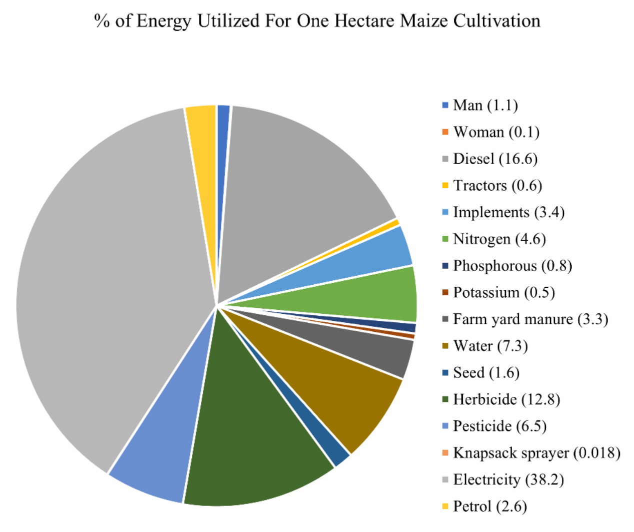

Fig. 4 : Energy utilization for maize cultivation

The energy input distribution for one hectare of maize cultivation reveals a system characterized by heavy reliance on electrical and fossil fuel-based energy. The largest share of energy use is attributed to electricity, comprising 38.2% of the total energy input. This substantial dependence likely stems from high irrigation requirements or postharvest handling involving electric-powered systems, emphasizing the need for more energy-efficient irrigation practices or potential use of renewable sources like solar pumps. Following electricity, diesel contributes 16.6%, pointing to considerable use of diesel-powered machinery for land preparation, sowing, or transport. This input alone signifies a mechanized operation and further suggests potential avenues for reducing emissions through fuel-efficient machinery or hybrid alternatives. Herbicide use (12.8%) represents another major contributor, suggesting strong reliance on chemical weed control, possibly due to labor shortages or weed infestations. Such chemical dependence, while operationally efficient, raises concerns about sustainability, resistance buildup, and environmental safety, warranting consideration of integrated weed management practices. The energy input from water (7.3%), pesticides (6.5%), and nitrogen fertilizer (4.6%) highlights additional areas of input intensity. While nitrogen use in maize is expected due to its role in vegetative growth and grain yield, its proportion here is lower than in crops like cotton. Nonetheless, optimizing its application through precision nutrient strategies remains crucial. Lesser but important shares include implements (3.4%), farmyard manure (3.3%), and petrol (2.6%), supporting routine mechanized tasks and supplementary nutrient management. Inputs like seed (1.6%), man labor (1.1%), potassium (0.5%), and phosphorus (0.8%) reflect foundational agronomic needs with relatively minimal energy costs. The very small contributions from women labor (0.1%), tractors (0.6%), and knapsack sprayers (0.018%) suggest infrequent use or lesser energy intensity in those areas. The maize energy input structure illustrates a system with high dependence on non-renewable energy sources, particularly electricity and diesel. This underscores the importance of transitioning toward sustainable energy inputs, mechanization efficiency, and eco-friendly agronomic practices to ensure productivity while minimizing ecological impacts and long-term energy costs.

Energy utilization for cotton cultivation

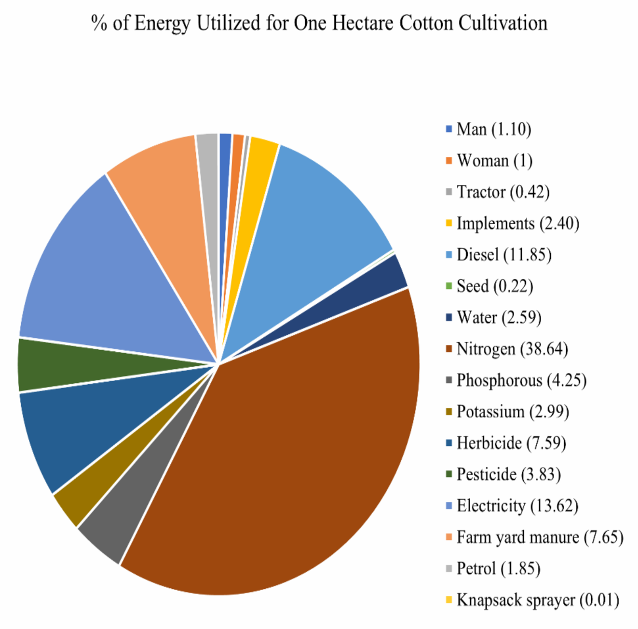

Fig. 5 : Energy utilization for cotton cultivation

The energy input analysis for one hectare of cotton cultivation reveals a highly input-intensive system dominated by synthetic fertilizer usage, particularly nitrogen, which alone accounts for 38.64% of the total energy input. This overwhelming share highlights the crop's significant nitrogen requirement and the energy burden associated with nitrogen fertilizer production and application. While nitrogen is essential for vigorous vegetative growth and boll formation, excessive reliance on it raises concerns about both economic efficiency and environmental impact, such as nitrate leaching and greenhouse gas emissions. Following nitrogen, electricity (13.62%) and diesel (11.85%) are the next major energy contributors, reflecting the use of powered equipment for irrigation, land preparation, and possibly ginning or postharvest processing. The combined share of these energy sources emphasizes the mechanized nature of cotton cultivation and points to the need for energy optimization practices, such as energy-efficient pumps or solar alternatives. Farmyard manure (7.65%), herbicides (7.59%), and phosphorus (4.25%) also account for considerable shares. The notable energy share of herbicides indicates a dependency on chemical weed control, likely due to limited manual weeding or labor availability. Meanwhile, farmyard manure input is commendable, suggesting a partial reliance on organic fertilization, which may help improve soil health and reduce synthetic input dependence over time. Smaller yet essential contributors include potassium (2.99%), water (2.59%), implements (2.40%), pesticides (3.83%), and petrol (1.85%), each supporting critical aspects of crop development and protection. Human labor, including man (1.10%) and woman (1%), represents a modest share, showing that although some manual operations persist, the system leans toward semi-mechanization. Negligible inputs like seed (0.22%), tractor (0.42%), and knapsack sprayer (0.01%) suggest limited frequency or energy intensity associated with their use. The overall profile of energy use in cotton farming underscores a highly input-dependent, mechanized system. This points to the urgent need for adopting integrated nutrient and pest management, precision agriculture, and sustainable energy solutions to enhance productivity while minimizing environmental footprints.

Energy utilization for Cassava cultivation

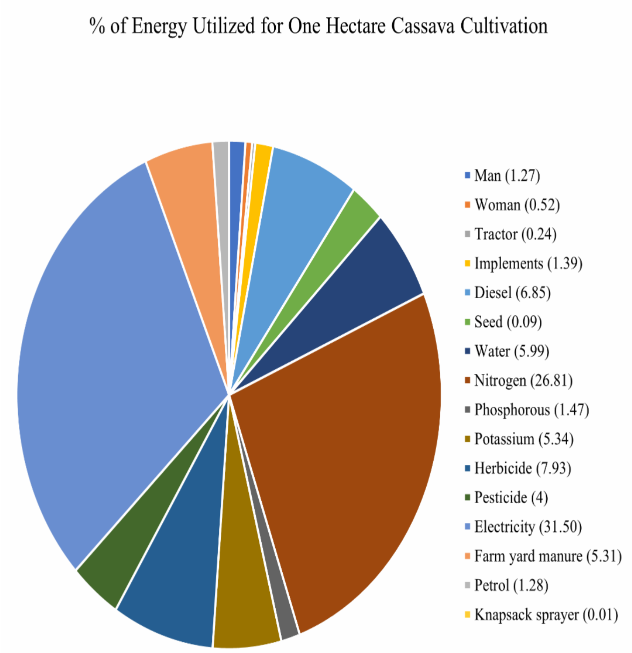

Fig. 6 : Energy utilization for Cassava cultivation

The energy utilization profile for one hectare of cassava cultivation reveals significant variation in input contributions across different sources. The highest share of energy input is from electricity (31.50%), indicating a heavy reliance on electrically powered irrigation or processing equipment. This suggests a need for efficient energy management practices or alternative energy sources like solar-powered systems to reduce dependency on the grid. Nitrogen fertilizer follows closely, contributing 26.81% of the total energy input. This reflects the intensive nutrient requirement of cassava for optimum growth and highlights the substantial energy cost associated with synthetic fertilizer production and application. Herbicides (7.93%) and diesel (6.85%)

also constitute notable energy inputs, indicating moderate use of chemical weed control and fuel-powered operations such as land preparation or transportation. Other important contributors include water (5.99%), potassium (5.34%), and farmyard manure (5.31%), which together show the combined importance of irrigation, balanced fertilization, and organic matter in cassava cultivation. Interestingly, manual labor (man: 1.27%, woman: 0.52%) and mechanical implements (tractor: 0.24%, petrol: 1.28%, implements: 1.39%) represent a relatively smaller proportion of the total energy budget, suggesting a semi-mechanized and input-intensive cultivation model with moderate human intervention. Minor inputs like seed (0.09%), knapsack sprayer (0.01%), and phosphorus (1.47%) account for a minimal fraction of energy utilization, reflecting their lower energy intensity or limited quantity of use. The low percentage of pesticide use (4%) might suggest either effective pest management strategies or a lower pest pressure in cassava fields. The findings underscore that cassava production is highly energy-intensive, particularly in terms of electricity and nitrogen use. There is significant potential for improving energy efficiency through the adoption of energy-saving technologies, integrated nutrient management, and sustainable agronomic practices. Reducing reliance on synthetic inputs and optimizing irrigation could substantially enhance the sustainability of cassava cultivation in the long term.

Energy utilization for Groundnut cultivation

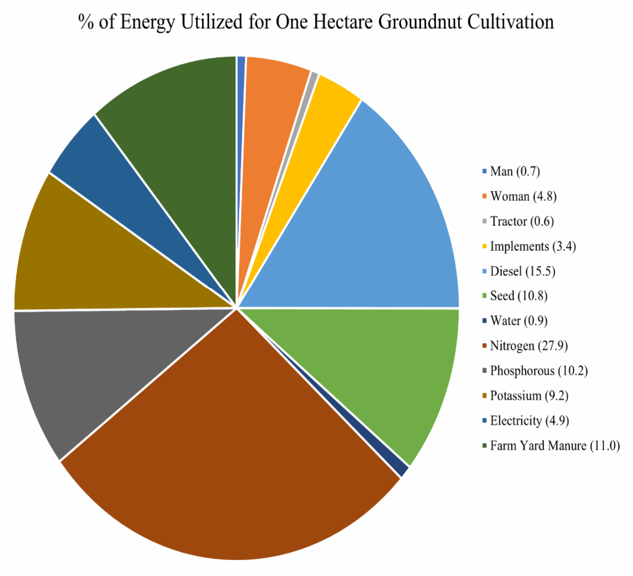

Fig. 7 : Energy utilization for Groudnut cultivation

The energy utilization pattern for one hectare of groundnut cultivation reflects a more balanced distribution compared to some other crops, with significant emphasis on nutrient inputs and fossil fuel-based operations. The highest proportion of energy use is associated with nitrogen fertilizer, contributing 27.9%, highlighting the importance of nitrogen in promoting vigorous vegetative growth and pod formation in groundnut plants. This high share underscores the need for precision nutrient management to optimize use and reduce potential runoff. Following nitrogen, diesel (15.5%) accounts for a major portion, indicating extensive reliance on diesel-powered machinery, possibly for plowing, sowing, or irrigation pumping. This is consistent with medium to high mechanization levels typical of oilseed crop cultivation. Notably, seed input contributes 10.8%, a relatively high figure compared to other crops, pointing to the use of high-density planting or potentially expensive improved seed varieties. Similarly, farm yard manure (11.0%) is a significant contributor, suggesting that organic nutrient supplementation plays a critical role in groundnut farming, either due to soil fertility needs or sustainable farming practices. The phosphorous (10.2%) and potassium (9.2%) inputs also reflect the crop's nutrient demand, reinforcing the importance of balanced fertilization in achieving optimal yields. This nutrient-focused energy use pattern aligns with groundnut's classification as a legume with specific macro- and micronutrient requirements. Implements (3.4%), electricity (4.9%), and woman labor (4.8%) also play notable roles. Interestingly, women's labor input is higher than male labor (4.8% vs. 0.7%), indicating gendered labor roles in groundnut farming, possibly in sowing, weeding, or harvesting activities. Tractor use is relatively low (0.6%), which might suggest limited mechanized field operations beyond initial land preparation. Water usage is also minimal (0.9%), indicating that groundnut is likely grown in rainfed conditions or requires little irrigation. The groundnut cultivation involves a nutrient-intensive energy profile, with major reliance on diesel fuel, fertilizers, and organic manure. The presence of significant female labor input and moderate use of implements and electricity points to a semi-mechanized, input-responsive farming system. These findings highlight the importance of efficient nutrient management, balanced mechanization, and sustainable organic input use for optimizing productivity and energy use in groundnut cultivation.

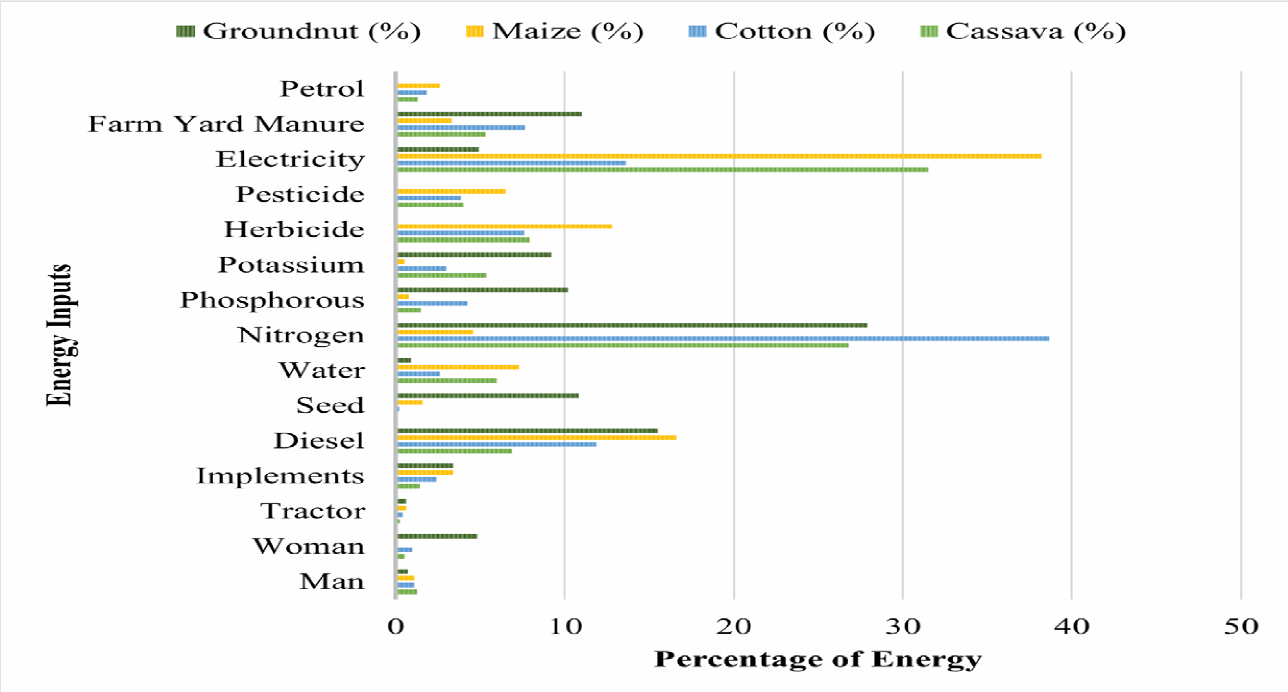

Fig. 8 : % of Energy Utilized for One Hectare Cultivation (Comparison Chart)

Energy Output

Table 4 : Energy Output for One Hectare Cultivation

Parameter	Maize	Cotton	Cassava	Groundnut
Grain Yield (kg/ha)	5000	447	45000	1250
Energy Equivalent Value (MJ/kg)	14.7	54.5	14.9	25.0
Output Energy (MJ/ha)	73,500	24,361.5	670,500	31,250
Input Energy (MJ/ha)	22,653.63	19,332.91	55,846.82	13,440.95
Energy Use Efficiency (%)	3.25	1.26	11.70	2.32
Energy Productivity (kg/MJ)	0.221	0.023	0.785	0.093
Net Energy (MJ/ha)	50,846.37	4,028.59	613,203.18	17,809.05

The comparison of energy use among maize, cotton, cassava, and groundnut cultivation reveals significant differences in their energy efficiencies and overall sustainability. Cassava emerges as the most energy-efficient crop, with the highest energy use efficiency (11.70%), energy productivity (0.785 kg/MJ), and net energy gain (613,203 MJ/ha), primarily due to its high yield and moderate energy input. Maize follows with a balanced energy profile, showing decent energy use efficiency (3.25%) and net energy (50,846.37 MJ/ha), making it both productive and energy-resilient. Groundnut performs moderately well with an energy use efficiency of 2.32% and a net energy of 17,809.05 MJ/ha, indicating a good balance between input and output despite a lower yield. In contrast, cotton demonstrates the lowest performance in all energy metrics, with only 1.26% energy use efficiency and minimal net energy gain (4,028.59 MJ/ha), suggesting that it is the least sustainable of the four in terms of energy utilization. These findings highlight cassava and maize as more energy-efficient options for sustainable agricultural practices.

Conclusion

The comparative energy analysis of maize, cotton, cassava, and groundnut revealed significant differences in energy use efficiency, productivity, and net energy output. Among the four crops, cassava emerged as the most energy-efficient, with the highest energy use efficiency (11.70%), energy productivity (0.785 kg/MJ), and net energy gain (613,203 MJ/ha), indicating its strong potential for sustainable agricultural production. Maize also demonstrated favorable performance, while cotton, despite its high market value, exhibited the lowest energy efficiency and productivity, highlighting its energy-intensive nature. Groundnut presented moderate energy characteristics in comparison.

These findings emphasize the importance of conducting comprehensive energy audits in agriculture, which help identify the most energy-demanding operations and inputs in crop production. Energy auditing serves as a diagnostic tool for assessing input-output relationships, enabling farmers and policymakers to make informed decisions aimed at improving energy efficiency, reducing production costs, and minimizing environmental impacts. Integrating energy audits into regular farm management practices can promote the adoption of energy-saving technologies, better input management, and more sustainable cropping systems. Ultimately, such evaluations are vital for achieving long-term energy sustainability in agriculture and enhancing overall productivity.

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