IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Mathematical Modelling of Engineering Problems
Vol. 10, No. 5, October, 2023, pp. 1901-1906
Journal homepage: http://iieta.org/journals/mmep

Optimizing Energy Consumption in Legume Production to Mitigate Greenhouse Gas Emissions: An Empirical Investigation

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Special Issue: Hybrid Renewable Energy Systems and Integration

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https://doi.org/10.18280/mmep.100544

Received: 2 October 2022
Revised: 27 December 2022
Accepted: 25 January 2023
Available online: 27 October 2023

Keywords:
optimizing energy consumption, greenhouse gases emission, agriculture, legumes, data envelopment analysis

ABSTRACT

Owing to the escalating utilization of agricultural inputs, energy consumption and the associated greenhouse gas (GHG) emissions have seen a significant surge. Consequently, the optimization of energy usage to mitigate environmental pollutants has emerged as a critical focus. This study employs the Data Envelopment Analysis (DEA) methodology to optimize energy consumption and reduce GHG emissions in agricultural production. Data was collected through randomized, face-to-face interviews with 200 agricultural producers in Chennai, India, in 2021. The results revealed that the total energy input for legume production was 2000 MJ/HA^2 for seed, 29950 MJ/HA^2 for fertilizer, and 1065 MJ/HA^2 for machinery. Among the consumption components, nitrogen fertilizer, electricity, diesel fuel, and irrigation water accounted for 35%, 27%, 18%, and 9% of the total, respectively. However, under optimal input consumption conditions, the total energy requirement was determined to be 31678 MJ/HA^2. Accordingly, a saving of 2.36% in total energy consumption could be achieved without compromising yield. This research underscores the potential for energy optimization in agricultural practices, contributing significantly to GHG emission reduction efforts.

1. INTRODUCTION

Legumes, renowned for their substantial protein content, are integral components of both human and animal diets [1]. When incorporated into crop rotation with cereals, they enhance soil quality and productivity, concurrently reducing the likelihood of subsequent crop affliction by weeds, pests, and diseases [2]. After beans and lentils, field peas are recognized as the next most nutritious legumes [3]. FAO statistics indicate that India holds a leading position globally in legume cultivation and is second in legume production [4].

In contemporary agriculture, inputs such as chemical fertilizers, pesticides, and genetically modified seeds have been observed to directly impact crop yield, causing a shift in energy consumption patterns and a resultant depletion of nonrenewable resources [5]. However, the escalated use of energy inputs in agricultural production has engendered several deleterious ecological consequences, including the decimation of wildlife and contamination of water sources [6]. Further, agriculture contributes to approximately 15% of global greenhouse gas (GHG) emissions, a significant factor in the average global temperature increase observed over the past century due to excessive GHG emissions [7].

Given the constraints of natural resources and the adverse effects of various energy sources on human health and the environment, it is imperative to scrutinize energy consumption patterns and strive to reduce GHG emissions for effective utilization in the agricultural sector [8]. Modern optimization methods have emerged as pivotal tools for establishing correct patterns of energy consumption and mitigating greenhouse effects [9].

Optimization in a system is a process where alterations in input or output values can yield maximum profit or minimum loss. One of the widely used methods, Data Envelopment Analysis (DEA), facilitates the attainment of these high system goals [10]. The strength of DEA lies in its capacity to accommodate multiple inputs and outputs, incorporating returns to scale into efficiency calculations, thus allowing for the concept of increasing or decreasing efficiency based on size and output levels [11]. DEA's four main models—Variable Returns to Scale (VRS), Constant Returns to Scale (CRS), Increasing Returns to Scale (IRS), and Decreasing Returns to Scale (DRS)—each have two directions of study: output-oriented and input-oriented [12, 13]. The input-oriented model examines how inputs should be reduced, keeping output constant, to reach optimal efficiency. The output-oriented model, conversely, aims to maximize output with constant input until the unit reaches optimal efficiency.

Various studies have been conducted on optimizing energy consumption and reducing greenhouse effects [14-18]. A comparative study of energy efficiency in legume, sunflower, and wheat crops was conducted in France [19]. Hamilton et al. identified gasoline, edible seeds, and agricultural machines as the most consumed inputs [20]. The labor force, consumable seeds, chemical fertilizers, and chemical pesticides accounted for the largest share of energy consumption [21]. In a study optimizing energy consumption and GHG emissions in cucumber production using the DEA method, a 10% reduction in energy consumption and a 7.98% reduction in greenhouse emissions were achieved compared to the initial state [8]. However, a thorough review of related sources reveals that despite the extensive research on energy consumption of legumes in agriculture, none have addressed this category from the perspective of GHG emissions, the ensuing environmental consequences, and the optimization of related pollutant emissions [22].

Consequently, the primary objective of this study is to employ DEA to optimize energy consumption and mitigate the impacts of GHG emissions in the legume production system in Chennai, India.

2. METHOD

Primary information was obtained by completing questionnaires and face-to-face interviews with legumes farmers Chennai, India. In order to collect the required data, the research questionnaire contained questions about the consumption of legumes production inputs in the region (diesel fuel, irrigation water, labor force, agricultural machinery, etc.) due to the large size of the community. In this study, a simple random sampling method was used to dispread the questionnaire. After collecting data related questionnaires, the energy ratio index was used to measure the standard deviation. Then, the required sample volume for the legumes product was calculated using Cochran's Equation [23]. Eq. (1) was estimated to increase the accuracy, the number of questionnaires was considered to be 200 samples.

$$n = \frac{N \times S^2 \times t^2}{(N-1)d^2 + (S^2 \times t^2)} \qquad d = \frac{(t \times s)}{\sqrt{n}} \tag{1}$$

where, N is the size of the statistical sample or the number of legumes farmers in the study area, t is the acceptable confidence coefficient, which is obtained from the student's t table assuming the distribution of the desired trait is normal; S is the estimate of the variance of the studied trait in the community, d is the desired possible accuracy (half of the confidence interval) and n is the sample size. This study is carried out following the study that has been conducted on the modeling of energy and economic indicators in the production of legumes and field peas. Based on this, the energy equivalents and the amount of consumption of each of the inputs in the production of legumes were adapted. The energy consumption in the two inputs of agricultural machines and irrigation water is calculated from Eqs. (2)-(3), respectively [24].

$$\mathrm{ME} = \frac{\mathrm{G} \times \mathrm{M_p} \times \mathrm{t}}{\mathrm{T}} \tag{2}$$

where, ME is the energy of the machine per unit area (MJ/HA^2), G is the mass of the machine (kg), M_P is the equivalent of the machine (mega joules per kilogram), t is the time of using the machine (hours per hectare) and T is the useful life of the machine (hour) is:

$$\mathrm{IE} = \frac{\mathrm{d} \times \mathrm{g} \times \mathrm{H} \times \mathrm{Q}}{\eta_1 \times \eta_2} \tag{3}$$

The processes of production, transportation, formation, storage, distribution and application of agricultural inputs on the one hand and the consumption of fossil fuels due to the use of agricultural machines on the other hand, cause the release of carbon dioxide gas and other greenhouse emissions into the atmosphere. In this study, the amount of carbon dioxide gas emission resulting from the consumption of inputs of agricultural machines, diesel fuel, electricity, fertilizers and chemical poisons was calculated from the product of the values of each of the inputs by the emission coefficients of that input per hectare. The amount of consumption of each input in the production of legumes and the corresponding emission coefficients are shown in Table 1.

Table 1. Coefficients and amount of GHG emissions in the production of legumes

References	GHG Emission Factor (Kg)	Input Consumption (/HA^2)	Input
Dyer and Desjardins [25]	0.054	631.7	Machine
Lal [26]	1.3	134.31	Fertilizer
	5.1	5.13	Chemical poison
	2.760	108.39	Diesel fuel
	0.608	565	Electricity

In this study, data coverage analysis was used in three models of technical efficiency, net technical efficiency and scale efficiency in order to calculate the optimized values of energy consumption and greenhouse emissions in the blue legumes product. In general, the definition of efficiency used in coverage analysis models is as follows [27]:

$$\frac{Total\ weighted\ output}{Total\ weighted\ input} = \text{Performance} \tag{4}$$

Technical efficiency (h_k), which is introduced based on the constant return to scale model, is basically measured by units evaluated for their performance, which is dependent on other units. This type of efficiency can be calculated from the following equation, which is the same as the linear programming model in Eq. (5):

$$\text{Max } h_k = \frac{\sum_{r=1}^{s} (u_{rk} y_{rk})}{\sum_{i=1}^{m} (v_{ik} x_{ik})};$$
$$\frac{\sum_{r=1}^{s} (u_{rk} y_{rk})}{\sum_{i=1}^{m} (v_{ik} x_{ik})} \leq 1; \quad (5)$$
$$j = 1, \dots, n$$
$$u_{rk}, y_{rk} \geq 0;$$
$$r = 1, \dots, s;$$
$$i = 1, \dots, m$$

Net technical efficiency is the same technical efficiency that is affected by the displacement of scale efficiency based on the variable returns to scale model. In this model, by changing one unit in the inputs, the output increases or decreases with a variable ratio.

When the values of technical efficiency and net technical efficiency are the same, it indicates scale efficiency, otherwise the scale parameter is inefficient. It is worth mentioning that farmers who have technical efficiency equal to one must also have net technical efficiency equal to one. Therefore, when agriculture has a technical efficiency less than one, it means that they are not on the constant return to scale line, and to determine the type of return to scale (incremental or decreasing), an additional test is needed. Accordingly, if the results of the return model If the decreasing scale and the variable returns to scale model are close to each other, in this case, the farmers with net technical efficiency have decreasing returns to scale, and otherwise, their returns to scale are increasing. In order to analyze the data, first the data were prepared in the form of a worksheet before implementation so that he could understand them. The farms were evaluated in terms of energy consumption and production performance as well as the trend of GHG emissions. Then the efficient and inefficient units were identified and the amount of input energy and Greenhouse emissions were calculated in the optimal state and their difference with the actual state was determined.

3. RESULT AND DISCUSSION

The total energy input and output in the production of legumes were calculated as 2000, 29950, and 1065 MJ/HA^2, respectively, for seed, fertilizer and machine (The most effective items on the energy consumption). As shown in Figure 1, nitrogen fertilizer, electricity, diesel fuel, and irrigation water have the largest shares among consumption inputs with 35%, 27%, 18%, and 9% respectively. The consumption of nitrogen fertilizer, as the most consumed input, is rooted in the false beliefs of farmers in this region. Appropriate and optimal use of fertilizers and knowledge of the compounds used in them can have a significant effect on reducing fertilizer consumption. In this area, almost the entire electricity input is used for pumping irrigation water. The lack of correct selection of irrigation pumps for extracting water from wells has been one of the major problems in all farms, which causes pump inefficiency in high efficiency. Also, the highest amount of fuel consumption in the studied area is related to tillage operations, which despite the low share of machines in the total energy input, a high amount of fuel is consumed during this process. This article indicates the low efficiency of machines due to lack of timely repair, lack of proper maintenance and lack of timely replacement. In a study, they evaluated the process of energy consumption in legumes cultivation. Based on the obtained results, the input and output energies were reported as 14514 and 25782 MJ/HA^2, respectively. Also, diesel fuel and irrigation water accounted for 29% and 30% of the total input energy in legumes production, respectively. In another research, the energy consumption trend in legumes production was compared for two organic and conventional crops. The results showed that the total input energy for conventional and organic cultivation was calculated as 5078 and 6191 MJ/HA^2, respectively; while the energy ratio for organic cultivation (2.5) was obtained more than integrated cultivation (2). Also, diesel fuel and seeds consumed in both cultures were recognized as the most consumed inputs.

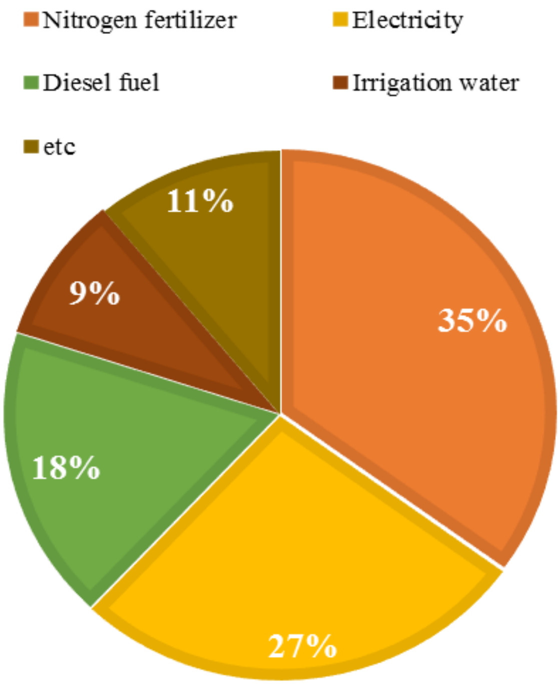

Figure 1. Consumption inputs in the production of legumes in the study area

Table 2. Amounts of actual and optimal energy consumption equivalent to different inputs in the production of legumes

Optimal Energy Consumption (MJ/HA^2)	Actual Energy Consumption (MJ/HA^2)	Standard Deviation (SD)	Institution
1765	2000	92	Seed
28956	29950	3432	Fertilizer
957	1065	200	Machine

In Table 2, the amounts of energy required in the state of optimal energy consumption for the production of legumes in the target area are shown. As the results show, the total amount of energy required in the state of optimal consumption of inputs was equal to 31678 MJ/HA^2. Therefore, it is possible to save 2.36% of the total input energy without reducing the performance. The contribution of each of the energy inputs in the total amount of stored energy is shown in Figure 2 using the rate of return to variable scale model. Based on this, inputs of irrigation water, nitrogen fertilizer and fertilizer have the largest share of the total stored energy with 20.26%, 18.56% and 12% respectively. In order to reduce the energy consumption equivalent to irrigation, it is recommended that the traditional irrigation systems in legumes cultivation be revised and the irrigation efficiency in the legumes farms of the study area be increased as much as possible. For this purpose, the integration of fields, proper leveling of land and creating a suitable slope for irrigation can prepare the ground for the realization of this goal. Also, the comparison between the results of this research and the study conducted on the legumes product shows that the excessive use of chemical fertilizers is due to the lack of knowledge of the farmers about the correct amount of this input. Fertilization based on the needs of the plant, correct crop rotation of the studied crops with plants of the legume family, the use of compost fertilizers and green fertilizers can be useful in reducing the consumption of chemical fertilizers, especially nitrogen fertilizers.

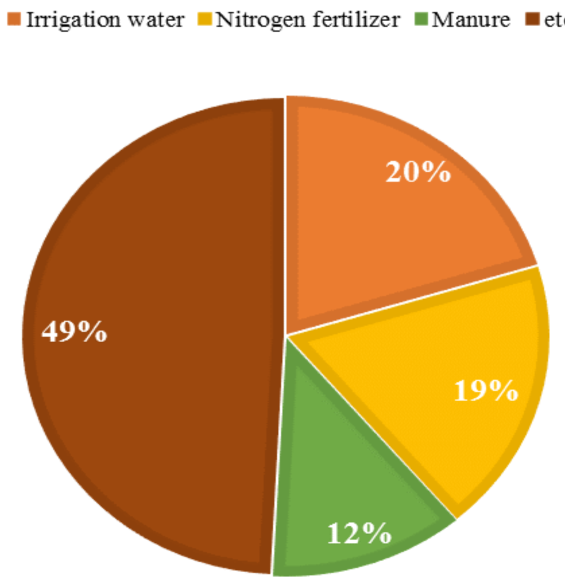

Figure 2. The contribution of different institutions in energy storage in legumes production with the method of rate of return to variable scale

Out of all 200 legumes producers, 110 farmers had a net technical efficiency of 1 using the variable return to scale model. Also, the technical efficiency of 55 farmers was equal to 1 based on the return to constant scale model. Therefore, 55 farmers have a net technical efficiency of 1 and a technical efficiency of less than 1, and this difference is due to the inappropriate production scale for them. Also, the scale efficiency of 77 farmers was equal to 1. In addition, from the total number of ineffective farmers, 31 and 77 farmers had net technical efficiency and technical efficiency in the range of 0.9 to 1, respectively.

The average values of different efficiencies and their standard deviation for legumes product producers are presented in Table 3. As can be seen, the values of technical efficiency, net technical efficiency and scale efficiency for farmers were determined as 0.1, 0.2 and 0.97, respectively. According to the standard deviation values, the technical efficiency dispersion is much higher than the net technical efficiency. This result shows that all farmers did not know about the correct production methods or did not use different inputs at the right time and in the optimal amount.

The contribution of each of the consumption inputs in reducing the potential of greenhouse emissions is shown in Figure 3. According to this form of electricity consumption, diesel fuel and nitrogen fertilizer have the greatest potential to reduce greenhouse emissions with 25%, 30% and 19% of the total share of reduced emissions, respectively.

Table 3. Different values of different efficiency of farmers in energy consumption for legumes production

Maximum	At Least	Average	Title
1	0.04	0.1	Technical efficiency
1	0.087	0.2	Net technical efficiency
1	0.054	0.97	Scale efficiency

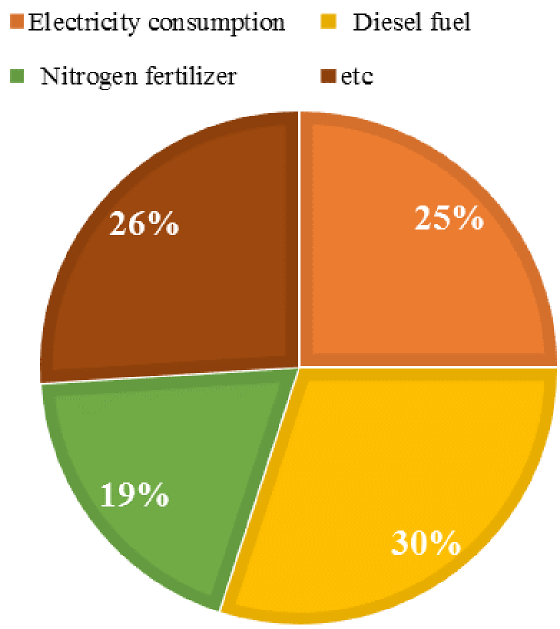

Figure 3. The contribution of production inputs in reducing GHG emissions in legumes production with the optimal use of production inputs

4. CONCLUSION

In this study, the Data Envelopment Analysis (DEA) technique was employed to address the dual objectives of decreasing total greenhouse gas emissions and enhancing overall productivity within the legume production system. These goals were identified as significant during the course of the research. Notably, certain farmers employing the models of returns to fixed and variable scales experienced a direct increase in productivity, while others did not observe a similar upward trend, highlighting the variable impacts of these models.

Water used for irrigation and nitrogen fertilizer were found to comprise the largest portions of the total stored energy, with respective shares of 20.26% and 18.56%. The rise in energy consumption in this region can be attributed to several factors, including inefficient irrigation systems, the use of electric motors nearing the end of their operational lifespan, and a lack of knowledge among farmers regarding the actual water requirements of the plants.

Moreover, the continued use of electric motors past their serviceable life further contributes to this increase in energy consumption. Consequently, it is strongly recommended that the irrigation sector conducts an investigation into its aging infrastructure.

Significant reductions in greenhouse gas emissions can be achieved through the management of chemical fertilizer consumption, applied research to ascertain the plant's nutritional needs at different growth stages, and the determination of the appropriate amount of chemical fertilizer required by the soil using soil testing. These measures not only regulate the application of chemical fertilizer, but also help to reduce the energy required to operate this input.

In conclusion, it is evident that a multifaceted approach, integrating optimized irrigation techniques, efficient use of machinery, and informed fertilizer application, is necessary to reduce greenhouse gas emissions and enhance productivity in the legume production system. The findings of this study provide valuable insights for future research and have significant implications for sustainable agricultural practices.

ACKNOWLEDGMENT

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University, Abha, Kingdom of Saudi Arabia for funding this work through Large Groups RGP.2/119/43.

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