

## Article

# Determination of Energy Consumption and Technical Efficiency of Cotton Farms in Türkiye

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**Abstract:** This study aimed to examine the efficiency of cotton farms and the energy requirements of the input and output of cotton in Türkiye. Data were collected from 657 cotton farms, and the results showed that the energy input of machinery (28.69%) had the most significant share in the total energy input, followed by electricity (22.79%) and nitrogen (20.75%). The total energy consumption of cotton was 83,869.49 MJ ha<sup>-1</sup>. In cotton production, the energy use efficiency, energy productivity, specific energy, and net energy were measured to be 0.87, 0.07, 17.31, and −23,043.92 MJ per hectare. Cotton plants consumed more indirect energy (51.99%) than direct energy (48.01%) and more non-renewable energy (89.96%) than renewable energy (10.04%). According to the data envelopment analysis results, the average technical efficiency of cotton farms was 0.84. Inefficient farms can reduce their inputs by approximately 16% without reducing the amount of cotton production. Allocative efficiency, pure technical efficiency, and scale efficiency of cotton farms were determined at 0.570, 0.539, and 0.640, respectively. Human labour, machinery, diesel, nitrogen, and phosphate energy use should be reduced for inefficient farms to become more efficient.

**Keywords:** agriculture; cotton; energy consumption; farmers; technical efficiency



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## 1. Introduction

Energy is one of the most critical inputs for the continuity of agricultural production. Agriculture uses energy to operate machinery and equipment, apply chemicals like pesticides and fertilizers, and heat and cool farm buildings [1]. In recent years, with the increase in the world population, the demand for food has grown, significantly increasing the amount of energy used in agriculture [2]. Thus, researchers' interest in using energy in agriculture has increased [3].

The efficient use of energy in agriculture is essential for ensuring agricultural sustainability [4]; however, using fossil fuels to increase efficiency in agricultural production plays a crucial role in increasing greenhouse gases [5,6]. Many researchers in different parts of the world have reported that the world is significantly affected by environmental pollution because of energy inputs used in agriculture [7–11]. Some countries with large surface measurements (China and the USA) have given importance to research reducing the use of fossil fuels used as energy sources in agricultural production [3,12,13]. Using energy in the right place and time will minimize environmental damage [14] and contribute to sustainable agricultural production [15]. Energy analysis is the first step in ensuring the most effective use of energy inputs in crop production [16]. Conducting energy analyses of agricultural products determines when, where, how, and why energy is used [16,17]. The information obtained from this analysis plays a vital role in reducing the production costs of farms [18].

Although the calculations related to energy use on the farm are complex [19], many studies have been carried out on this subject [20–27]. When analysing agricultural input/output energy ratios, caution is required. Determining the best management strategies for farm products is related to calculating energy input data and many other factors [28].

Cotton requires the highest energy input among annual plants in agricultural production [29].

Cotton, the most produced natural fibre in the world, is known for its wide usage area [30]. World cotton production is approximately 73.7 million tons. The top five countries with the highest cotton production are China (17.4 million tons), India (17.2 million tons), the USA (11.2 million tons), Brazil (5.7 million tons), and Pakistan (4.1 million tons). These five countries produce 75.4% of the total cotton. Türkiye, ranking seventh in world cotton production, provides 3.1% of world production [31]. Considering that cotton cultivation requires high energy inputs, it is necessary to conduct research to increase energy efficiency in production. Studies on energy consumption in cotton have been carried out in various countries [32–42]; however, no study has investigated farms' energy consumption and efficiency in the five provinces with the highest cotton production in Türkiye. In recent years, with the mechanisation of cotton agriculture, the production style has changed; accordingly, the number of inputs used in the production area has also changed. Manual harvesting has been replaced almost entirely by machine harvesting. Therefore, there have been significant changes in energy use in cotton agriculture as of 2021. The use of fossil fuels has increased, especially with the spread of mechanisation in cotton production. In this context, energy consumption analysis can be a useful indicator to ensure sustainable agricultural production, as it contains information about how much fossil fuel is consumed in production [43].

It may be helpful to measure farm-level economic, technical, and allocative efficiency and its determinants to develop suitable policy measures that will allow cotton farms to increase productivity through improved efficiency [44]. Many studies have been conducted to calculate the efficiency of farms [44–54]. Technical efficiency analysis comes first among the methods used to measure the productivity of businesses [55]. Technical efficiency analyses (TEA) are often used to measure the contribution of production technology and agricultural inputs to production [51]. Many different methodologies have been proposed for measuring the TEAs of farms [56–58]. Data envelopment analysis is one of the most widely used analyses in this field [51].

This study examined the energy needs of inputs and outputs in cotton production. In addition, values for energy use efficiency, energy productivity, net energy, specific energy, direct energy, indirect energy, renewable energy, and non-renewable energy were all calculated. Finally, the efficiency of the farms was found by using data envelopment analysis.

## 2. Material and Methods

### 2.1. Study Area

This study was conducted in the Sanliurfa, Aydin, Hatay, Diyarbakir, and Adana provinces, which account for 80% of the total cotton production in Türkiye (Figure 1). Sanliurfa province, located in the southeast of Türkiye, has a continental (terrestrial) climate; the summers are scorching and dry, and the winters are rainy and mild. The number of days with snow and frost is very few. Agricultural production is carried out on 56.2% of the province's surface area and has 1.04 million decares of agricultural areas, constituting 4.45% of the total agricultural land in Türkiye. In this province, most of the agricultural land, accounting for 69.5%, is designated for producing cereals and other plant-based products. Additionally, 17.6% of the land is allocated for cotton production. Sanliurfa contains 42.4% of the cotton production in Türkiye. Diyarbakir province, located in the southeastern Anatolia region, has a flat structure in terms of landforms. It has a harsh continental climate, with hot and dry summers and cold and rainy winters. Along with the GAP project, many dams were built around Diyarbakir that contribute to the irrigation of agricultural areas. Diyarbakir contains 12.8% of the cotton production in Türkiye. In Aydin, where the Mediterranean climate dominates, summers are hot and dry, and winters are warm and rainy. Because it has a coast along the Aegean Sea, the warming effect of the sea and the winds that bring precipitation from the sea are dominant in the province. It is colder

than the Mediterranean region due to northerly winds and the occasional snowfall. Aydın has 11.4% of the cotton production in Türkiye. Hatay has a bridge connecting Mesopotamia to the Mediterranean in the southern part of the country. The Mediterranean climate is dominant, with hot and dry summers and mild and rainy winters. Hatay agricultural production lands are about 54.7% of its total land area. The cotton production of Hatay meets around 9.1% of the total cotton production of Türkiye. The most important plain in the province is the Amik Plain, which is highly developed in agriculture. In Adana, influenced by the Mediterranean climate, the summers are hot and dry, and the winters are warm and rainy. Adana has 4.9 million decares of agricultural land. Seventy-three per cent of the Çukurova region is within the provincial borders of Adana, and it is very productive in agricultural production due to the alluvial soils carried by the Seyhan and Ceyhan rivers. Agricultural production is in 34.7% of the provincial area. The Adana province contains 5.1% of the cotton produced in Türkiye [59].



**Figure 1.** Study area location map.

## 2.2. Sampling

The data used in this study were collected through face-to-face interviews with 657 cotton producers in the research region in the cotton production season of 2021 (Table 1). The sample number determined for the questionnaire was calculated with the proportional sampling method [60]. The sample size was calculated with a 99% confidence interval and a 5% margin of error (1):

$$n = \frac{Np(1-p)}{(N-1) * \sigma_{px}^2 + p(1-p)} = 657 \quad (1)$$

where  $n$  is the sample size,  $N$  is the number of producers,  $\sigma_{px}^2$  is the variance of the ratio, and  $p$  is the ratio of cotton producers ( $p = 0.5$  to reach the maximum sample size). The

survey numbers are distributed proportionally to the number of producers in the provinces, as shown in Table 1.

**Table 1.** Distribution of surveys.

| Region                | Province   | Number of Farmers | Number of Farmers Surveyed |
|-----------------------|------------|-------------------|----------------------------|
| Southeastern Anatolia | Sanliurfa  | 28,613            | 377                        |
| Aegean                | Aydin      | 8078              | 106                        |
| Mediterranean         | Hatay      | 6142              | 81                         |
| Southeastern Anatolia | Diyarbakir | 3660              | 48                         |
| Mediterranean         | Adana      | 3396              | 45                         |
| Total                 |            | <b>49,889</b>     | <b>657</b>                 |

Reference: [61].

The survey questions were prepared after focus group discussions with cotton farmers in five provinces. The survey questions included information regarding field preparation, seeds, use of machinery and equipment, irrigation, fertilization, pesticides, energy, harvesting, storage, and post-harvest transport.

### 2.3. Cotton Crop Management

Farmers in the study area use the triple rotation system in cotton production. They usually prepare the field for cotton planting after the wheat harvest. Forage crops are grown after cotton.

In soil preparation, firstly, crushing is performed with a crushing machine. This process happens between October and December. The first version with the plough and the second with the bottom boiler occurs in December. Following this, ploughing is performed with the cultivator from February to April before planting. Cotton is grown in the Çukurova region from late March to mid-April and in other areas from late April to May. Hand hoeing and tractor hoeing are performed between May and June to remove weeds. During the hoeing process, dilution also happens. The dilution and misfire processes occur between May and June when the cotton plants reach 10 centimetres in length to accelerate the plants' development and maturation. One of the most critical applications to increase cotton yield is fertilization. This process happens between March and May. The second application is the spraying process between May and August [62]. In this study, they applied pesticides an average of 6.77 times. Cotton is a plant with a high need for water, and irrigation should be performed 4–5 times at intervals of 15–20 days between May and August. This study had an average of 6.34 irrigation. With the maturation of the cotton bolls, the harvest happens between September and November. Cotton is harvested by machine and by hand and then transported to ginning factories.

### 2.4. Energy Input–Output Analysis

Many studies have determined energy equivalents for various inputs. This study used equivalent energy inputs from related studies to calculate energy inputs for cotton production (Table 2). The energy consumed was calculated by multiplying the amount of input used by its energy equivalents. Energy productivity, energy use efficiency, specific energy, and net energy were calculated based on energy input and output.

**Table 2.** Energy equivalents of inputs and outputs.

|                         | Unit           | Energy Equivalent<br>(MJ Unit <sup>-1</sup> ) | References |
|-------------------------|----------------|---|------------|
| <b>A. Inputs</b>        |                |   |            |
| 1. Human labour         | h              | 1.96  | [19,35,41] |
| 2. Machinery            | h              | 62.70   | [33,40,63] |
| 3. Diesel fuel          | L              | 56.31   | [63]       |
| 4. Fertilizers          |                |   |            |
| (a) Nitrogen            | kg             | 60.60   | [33]       |
| (b) Phosphate           | kg             | 11.10   | [33]       |
| (c) Potassium           | kg             | 6.70  | [33]       |
| 5. Chemicals            |                |   |            |
| (a) Herbicides          | kg             | 238.00  | [33,35,64] |
| (b) Insektisit          | kg             | 101.20  | [33,35,64] |
| (c) Defoliant           | kg             | 101.20  | [33,35,64] |
| 6. Electricity          | kWh            | 3.60  | [38]       |
| 7. Water for irrigation | m <sup>3</sup> | 0.63  | [19]       |
| 8. Seed                 | kg             | 11.80   | [33]       |
| <b>B. Outputs</b>       |                |   |            |
| 1. Cotton grain yield   | kg             | 11.80   | [33]       |

The following formulas were used to calculate energy use efficiency (EUE), energy productivity (EP), net energy (NE), and specific energy (SE).

The ratio between energy output and input is EUE [65,66]. This process evaluated the system's efficiency [67–69].

$$EUE = \frac{\text{Energy output (MJha}^{-1}\text{)}}{\text{Energy input (MJ ha}^{-1}\text{)}} \quad (2)$$

Specific energy (SE) is the ratio of the energy input consumed to the product yield [70,71]. The following equation helped calculate the SE:

$$SE = \frac{\text{Energy input (MJ ha}^{-1}\text{)}}{\text{Product Output (kg ha}^{-1}\text{)}} \quad (3)$$

Energy productivity (EP) is the ratio of the output consumed to energy input [72,73]. The following equation helped calculate the EP:

$$EP = \frac{\text{Output kg (ha}^{-1}\text{)}}{\text{Energy input (MJ ha}^{-1}\text{)}} \quad (4)$$

You find the net energy (NE) by subtracting the energy consumed in the input from the energy obtained from the output [69,72,73].

$$NE = \text{Energy output (MJ ha}^{-1}\text{)} - \text{Energy input (MJ ha}^{-1}\text{)} \quad (5)$$

In addition, direct energy (human labour, diesel fuel, electricity, water), indirect energy (fertilisers, chemicals, machinery, seeds), renewable energy (human labour, seeds, water), and non-renewable energy (diesel fuel, electricity, chemicals, fertilisers, machinery) used in cotton production were calculated [35].

### 2.5. Data Envelopment Analysis (DEA)

Data from 657 farms were used to measure the efficiency of farms. In the research, data envelopment analysis (DEA), a non-parametric method, was used to measure the

production efficiency of cotton farms. Because farms generally tend to control inputs, Farrell's [74] input-oriented efficiency measures were used in this study.

The inputs ( $X_i$ ) used in the model are seed ( $\text{kg ha}^{-1}$ ), N ( $\text{kg ha}^{-1}$ ), P ( $\text{kg ha}^{-1}$ ), irrigation (time), spraying (time), human labour ( $\text{h ha}^{-1}$ ), and machinery ( $\text{h ha}^{-1}$ ). It is assumed that cotton ( $y_i$ ) is produced using the  $X_i$  inputs. Therefore, a seven-input single-output model was created. The economic efficiency towards the input for each farm can be found by solving the following linear programming model:

$$\min_{\lambda, x_i^*} W_i^T x_i^* \quad (6)$$

$$\text{limitations} - y_i + Y\lambda \geq 0$$

$$x_i^* - X\lambda \geq 0$$

$$\lambda \geq 0,$$

In the equation,  $W_i$  is the vector of an input price;  $T$  is the transpose of function; and  $x_i^*$  is the cost-minimizing vector of input quantities;  $y_i$ , the minimum cost of the input level, was calculated via linear programming for each farm. This equation shows the lowest cost to scale under constant returns.

The formula  $(EE) = W_i^T x_i^* / W_i^T x_i$  was used to calculate the economic efficiency of each farm. In other words, economic efficiency is the ratio of the lowest cost calculated under constant returns to scale to the observed cost for given input prices. The allocation efficiency was calculated with the formula  $AE = CE/TE$  [75]. The DEAP 2.1 program developed by Coelli [76] was used to estimate the efficiency measures. In comparison, for efficient and inefficient farms, farms with an efficiency coefficient between 0.90 and 1 were classified as efficient, and those lower than 0.90 were classified as ineffective [77]. The comparison of efficient and inefficient farms in terms of variables examined t-tests for continuous data.

### 3. Results and Discussion

#### 3.1. Energy Consumption in Production

The quantity of input and output and total input and output energy ( $\text{MJ ha}^{-1}$ ) in cotton production is presented in Table 3. The total input energy used in cotton production was calculated at  $83,869.49 \text{ MJ ha}^{-1}$ . Considering Türkiye, machinery had the highest share of energy consumption in cotton production (28.69%), followed by electricity (22.79%), nitrogen (20.75%), and diesel fuel (15.59%).

While producing cotton, a machine is needed at every stage, from planting preparation to harvest. Thanks to advanced machines, agricultural products are produced in a shorter time by consuming less energy [78]. In this study, the percentage of farmers harvesting cotton by machine was 91%. For this reason, machines are expected to have the highest use of energy in cotton farming.

Electrical energy is used in cotton production, tube well energizing, lighting, and irrigation. The use of electricity varies and mainly depends on the type of irrigation. Surface irrigation methods are generally used in cotton farming in Türkiye. When the drip irrigation method is used, electricity consumption will also decrease. This study stated that electrical energy consumed an average of  $19110.11 \text{ MJ ha}^{-1}$  for the cotton. Electricity use accounted for 22.79% of the total energy use in cotton production (Table 3). Another study stated that electricity (28%) consumed the most energy after fertilizer in cotton farming [34].

The use of chemical fertilizers has increased considerably in Türkiye, as well as in the world, to increase productivity. Previous researchers have reported that fertilizers account for most of the total energy input for cotton [35–37,40]. It was determined that  $223.17 \text{ kg ha}^{-1}$  fertilizer was used in cotton farming in Punjab [41],  $120.8 \text{ kg ha}^{-1}$  in Gorgan, and  $164.61 \text{ kg ha}^{-1}$  in Darab [40]. In the current study, the use of fertilizers was higher than in other countries. This result may be a way that cotton farmers resort to obtaining more products, or it may be due to the lack of knowledge about fertilization in cotton.

**Table 3.** Energy consumption of cotton.

|                         | Unit           | Energy Equivalent (MJ Unit <sup>-1</sup> ) | Input Used per Hectare (Unit ha <sup>-1</sup> ) | Energy Value | Ratio (%) |
|-------------------------|----------------|--|---|--------------|-----------|
| <b>A. Inputs</b>        |                |  |   |              |           |
| 1. Human labour         | h              | 1.96                                       | 585.94  | 1148.44      | 1.37      |
| 2. Machinery            | h              | 62.7                                       | 383.81  | 24,064.88    | 28.69     |
| 3. Diesel fuel          | L              | 56.31                                      | 232.26  | 13,078.52    | 15.59     |
| 4. Fertilizers          |                |  |   |              | 22.05     |
| (a) Nitrogen            | kg             | 60.6                                       | 287.19  | 17,403.77    | 20.75     |
| (b) Phosphate           | kg             | 11.1                                       | 95.84   | 1063.79      | 1.27      |
| (c) Potassium           | kg             | 6.7  | 3.48  | 23.31        | 0.03      |
| 5. Chemicals            |                |  |   |              | 0.84      |
| (a) Herbicides          | kg             | 238.0                                      | 1.6   | 380.59       | 0.45      |
| (b) İnsektisit          | kg             | 101.2                                      | 2.07  | 209.10       | 0.25      |
| (c) Defoliant           | kg             | 101.2                                      | 1.15  | 116.38       | 0.14      |
| 6. Electricity          | kWh            | 3.6  | 5308.36   | 19,110.11    | 22.79     |
| 7. Water for irrigation | m <sup>3</sup> | 0.63                                       | 10,995.22                                       | 6926.99      | 8.26      |
| 8. Seed                 | kg             | 11.8                                       | 29.12   | 343.6        | 0.41      |
| Total inputs            |                |  |   | 83,869.49    | 100.00    |
| <b>B. Output</b>        |                |  |   |              |           |
| 1. Cotton grain yield   | kg             | 11.8                                       | 5124.20   | 60,465.57    | 100.00    |
| Total output            |                |  |   | 60,465.57    | 100.00    |

Chemicals are used in cotton production for plant growth and disease and pest control. In recent years, there has been an increase in diseases and pests in cotton fields. For this reason, pesticide applications have increased [79] in cotton farming areas. Herbicides are used in the control of narrow-leaved weeds in cotton production and in the fight against insects, such as aphids, green worms, and red spiders. Insecticides and plant growth regulators, including boll openers and defoliant, are used to ensure the homogeneous opening of maturing cotton bolls and the shedding of leaves. Chemicals covered 0.89% of energy consumption. Herbicides (380.59 MJ ha<sup>-1</sup>) were found to be the most energy-consuming of chemicals.

Diesel fuel is commonly used in cotton farming, from irrigation to fertilization to harvesting to processing. In the research area, 232.26 lt ha<sup>-1</sup> of diesel was used during cotton cultivation. The energy value of this use was 13,078.52 MJ ha<sup>-1</sup>; the use of diesel accounted for 15.59% of the total energy consumption (Table 3). In a similar study, the average diesel fuel use per hectare in Pakistan was 78.35 lt ha<sup>-1</sup> [41]. This result confirmed that using diesel fuel machines increased cotton farming in Türkiye.

In recent years, hand harvesting has left its place for machine harvesting in cotton production in Türkiye. The percentage of farmers harvesting cotton by hand was 9%. For this reason, it was expected that machines result in the highest use of energy in cotton farming. The energy output of cotton yield was 60,465.57 MJ ha<sup>-1</sup>. In other studies, the cotton energy output was calculated as 36,729 MJ ha<sup>-1</sup>, 95,800 MJ ha<sup>-1</sup>, 36,189 MJ ha<sup>-1</sup>, 36,882 MJ ha<sup>-1</sup>, 56,050 MJ ha<sup>-1</sup>, 33,314 MJ ha<sup>-1</sup>, and 65,984 MJ ha<sup>-1</sup>, respectively [35,36,38–42]. The average cotton yield in the study area was 5124.2 kg ha<sup>-1</sup>, higher than in other countries except for China [31]. In addition, the mechanization of cotton production in Türkiye in recent years has caused the output energy to be higher than in other studies [35–37,39].

In the study area, more furrow irrigation techniques were used in cotton farming. Sprinkler and drip irrigation systems were used less frequently [80]. Because of the less effective use of water consumption, drip and sprinkler irrigation methods consume less energy than furrow irrigation methods [81]. According to the study results, an average of 10,995.22 m<sup>3</sup> ha<sup>-1</sup> water was consumed in cotton production. The energy consumed

for irrigation was  $6926.99 \text{ MJ ha}^{-1}$ . It was 8.26% of the energy consumption in cotton agriculture (Table 3).

Intensive soil cultivation is carried out in cotton farming (ploughing, planting, hoeing, etc.). Rusu [82] and Lachuga [83] reported that tillage constitutes a significant part of energy costs. For this reason, in cotton farming, it is thought that energy consumption can be reduced by using minimal tillage methods (stubble sowing, tillage, seed sowing with a single tool, etc.) instead of traditional tillage.

### 3.2. Energy Indices of Cotton Production

Energy use efficiency, energy productivity, specific energy, and net energy in cotton production are presented in Table 4. The energy use efficiency of cotton production in Türkiye was calculated at 0.87. This value showed that the energy use in cotton farming is inefficient. Reducing agricultural inputs or increasing the cotton yield is necessary to increase energy efficiency [40]. This is supported by Yilmaz et al. [35], who stated that the EUE in cotton farms in the Antalya province of Türkiye was 0.74. Gokdogan et al. [39] reported that the EUE in cotton farms in the Aydin province of Türkiye was 1.92. The EUE of cotton farms in the Sanliurfa province of Türkiye was calculated at 2.52 [36] and 2.36 [37]. The main reason for this difference in results is that climatic conditions have an impact on energy use efficiency. In other studies, Khan et al. [84] in China, Zahedi et al. [38] in Isfahan, Kazemi et al. [40] in Darab, Kazemi et al. [40] in Gorgan, and Imran et al. [41] in Punjab calculated the energy use efficiency in cotton as 1.51, 0.70, 0.94, 1.11, and 0.70, respectively.

**Table 4.** Energy indices of cotton production in Türkiye.

| Energy Indices                              | Mean       |
|---|------------|
| Energy use efficiency                       | 0.87       |
| Energy productivity ( $\text{kg MJ}^{-1}$ ) | 0.07       |
| Specific energy                             | 17.31      |
| Net energy ( $\text{MJ ha}^{-1}$ )          | −23,043.92 |

The energy productivity of cotton production in Türkiye was  $0.07 \text{ kg MJ}^{-1}$ . According to this finding, 0.07 units of output were obtained per unit of energy. Previous studies have shown that the energy productivity of cotton production in Isfahan was  $0.10 \text{ kg MJ}^{-1}$  [38] and 0.04 in Punjab [41]. Kazemi et al. [40] reported that the energy productivity of cotton farms in Darab was  $0.08 \text{ kg MJ}^{-1}$  and  $0.09 \text{ kg MJ}^{-1}$  in Gorgan.

The specific energy was  $17.31 \text{ MJ kg}^{-1}$ . This indicator was estimated at  $12.53 \text{ MJ kg}^{-1}$  for Darab and at  $10.67 \text{ MJ kg}^{-1}$  for Gorgan [40]. As for the rate of net energy, it was found to be  $-23,043.92 \text{ MJ ha}^{-1}$ . The negative value for net energy was also found by Zahedi et al. [38], Kazemi et al. [40], and Imran et al. [41] for cotton. Energy conservation in these fields can be improved by increasing energy efficiency and implementing new technologies. As long as the energy output per unit of energy input rises, net energy increases [40].

Total mean energy inputs as direct, indirect, renewable, and non-renewable are presented in Table 5. The results showed that cotton consumed more indirect energy (51.99%) than direct energy (48.01%). Similarly, Yilmaz et al. [35] and Zahedi et al. [38] found that cotton consumed more indirect energy than direct energy. However, Kazemi et al. [40] found the opposite result.

This study used human labour, seeds, and water as renewable energy sources. It was determined that renewable resources (10.04%) consumed less energy than non-renewable resources (89.96%). Yilmaz et al. [35] and Gokdogan et al. [39] also reported similar results. Because the energy consumption of renewable energy sources used in cotton production was low (Table 2), no significant energy savings are expected from these sources. However, considerable energy savings can be expected using non-renewable energy sources (machinery, diesel, nitrogen, etc.).

**Table 5.** Total energy input in the form of direct, indirect, renewable, and non-renewable energy sources for cotton production in Türkiye (MJ ha<sup>-1</sup>).

|                      | MJ ha <sup>-1</sup> | %      |
|----------------------|---------------------|--------|
| Direct energy        | 40,264.06           | 48.01  |
| Indirect energy      | 43,605.43           | 51.99  |
| Renewable energy     | 8419.03             | 10.04  |
| Non-renewable energy | 75,450.46           | 89.96  |
| Total input energy   | 83,869.49           | 100.00 |

Information about the descriptive statistics of the variables used in the efficiency analysis is presented in Table 6. A seven-input and single-output model was created to measure the cotton production efficiency of farms with DEA. To obtain an average cotton yield of 5124.2 ha kg<sup>-1</sup> of cotton during the cotton production season, an average of 29.16 kg ha<sup>-1</sup> of seeds, 287.19 kg ha<sup>-1</sup> of N, 95.84 kg ha<sup>-1</sup> of P, 6.33 times of irrigation, 6.78 times of spraying, 585.94 h of labour, and 383.81 h of machine power are needed.

**Table 6.** Descriptive statistics of the variables used in the efficiency analysis.

| Output and Inputs                    | Mean    | Std. Dev. | Min     | Max     |
|--------------------------------------|---------|-----------|---------|---------|
| Output                               |         |           |         |         |
| Yield (kg ha <sup>-1</sup> )         | 5124.20 | 962.56    | 1000.00 | 7800.00 |
| Inputs                               |         |           |         |         |
| Seed (kg ha <sup>-1</sup> )          | 29.16   | 5.47      | 10.00   | 6.00    |
| N (kg ha <sup>-1</sup> )             | 287.19  | 90.99     | 0.01    | 934.00  |
| P (kg ha <sup>-1</sup> )             | 95.84   | 56.94     | 0.01    | 330.00  |
| Irrigation (times ha <sup>-1</sup> ) | 6.33    | 2.35      | 2.00    | 10.00   |
| Spraying (times ha <sup>-1</sup> )   | 6.78    | 2.47      | 2.00    | 12.00   |
| Human labour (h ha <sup>-1</sup> )   | 585.94  | 336.00    | 56.95   | 2748.90 |
| Machinery (h ha <sup>-1</sup> )      | 383.81  | 214.04    | 36.95   | 2548.90 |

Economic, technical, allocation, scale, and pure technical efficiency values in cotton farms were estimated with DEA. The data obtained from the analysis are presented in Table 7. The economic efficiency in the examined cotton farms varied between 0.156 and 1, and the average was 0.479. According to the results, ineffective cotton farms should reduce their costs in the production process by approximately 52% to reach the level of effective cotton farms by producing in the minimum cost input composition. The main reason for the inefficiency in cotton farms was inadequate allocation efficiency. The allocation efficiency of the examined farms varied between 0.103 and 1, and the allocation efficiency coefficient was determined to be 0.570 on average. Cotton farms produced 43% more cost than the minimum cost input composition. This finding means that some cotton farms produce with the wrong input combination considering the current input prices and technology level.

**Table 7.** Efficiency analysis results of cotton farms.

| Efficiency                | Mean  | Std. Dvt. | Lower Limit | Upper Limit |
|---------------------------|-------|-----------|-------------|-------------|
| Economic efficiency       | 0.479 | 0.146     | 0.076       | 1.000       |
| Allocative efficiency     | 0.570 | 0.141     | 0.103       | 1.000       |
| Technical efficiency      | 0.838 | 0.116     | 0.572       | 1.000       |
| Scale efficiency          | 0.640 | 0.297     | 0.003       | 1.000       |
| Pure technical efficiency | 0.539 | 0.275     | 0.002       | 1.000       |

The technical efficiency of cotton farms varied between 0.116 and 1, and the technical efficiency coefficient was determined to be 0.838 on average. This result shows that

inefficient farms can reduce their inputs by approximately 16% without reducing cotton production. Pure technical efficiency and scale efficiency were used to determine the technical efficiency coefficient of the examined cotton farms, and they were determined to be 0.539 and 0.640, respectively. The main reason for the lack of technical efficiency in cotton farms was the technical inadequacy of cotton farmers' agricultural knowledge and skills. Although most of the examined farms were of appropriate scale, they could not technically carry out their activities. According to the results of the scale efficiency analysis, 85.8% (564 farms) of the cotton farms in the research area had increasing returns to scale, and 7.9% of those (52 farms) had decreasing returns to scale. In comparison, the rate of cotton farms with fixed returns to scale was 6.3% (41 farms). Binici et al. [85], in their study of cotton farmers in the Harran Plain, determined that 70% of the farms were operated ineffectively. In similar research, technical efficiencies in cotton farms in the Hatay and Adana provinces ranged from 0.23 to 1.00, and the average technical efficiency was determined to be 0.79 [47]. This result indicates that there are some opportunities to increase resource use efficiency. For instance, they can reduce their input costs by 21% on average to produce the same yield in cotton farms [47]. Wei et al. [86] found the technical efficiency, economic efficiency, and allocation efficiency of cotton mills in Punjab to be 0.95, 0.66, and 0.70, respectively. In a study comparing the technical efficiency of irrigated and non-irrigated cotton producers, it was found that 80% of irrigated cotton producers are efficient, and 70% of non-irrigated cotton producers are efficient. Findings showed that in Texas, irrigated farms can reduce their expenditure on inputs by 10% on average while producing at the same level [45].

The energy consumption of technically efficient and inefficient farms is presented in Table 8. Farms with an efficiency coefficient of  $<0.90$  were grouped as inefficient, and farms with  $\geq 0.90$  were grouped as efficient farms. For inefficient farms to be effective, energy consumption should be reduced in all other inputs except potassium. Statistically, for inefficient farms to become efficient farms, it is necessary to reduce the use of human labour, machinery, diesel fuel, nitrogen, and phosphate energy by 27.6%, 29.4%, 10%, 19%, and 32.6%, respectively ( $p < 0.01$ ).

**Table 8.** The energy consumption of technically efficient and inefficient farms.

|                             | Inefficient |            | Efficient |            | Difference (%) |
|-----------------------------|-------------|------------|-----------|------------|----------------|
|                             | Mean        | Std. Error | Mean      | Std. Error |                |
| <b>A. Inputs</b>            |             |            |           |            |                |
| 1. Human labour ***         | 1233.28     | 32.37      | 966.59    | 38.54      | −27.59         |
| 2. Machinery ***            | 25,941.11   | 692.61     | 20,043.11 | 627.58     | −29.43         |
| 3. Diesel fuel ***          | 13,468.04   | 188.33     | 12,243.57 | 257.14     | −10.00         |
| 4. Fertilizers              |             |            |           |            |                |
| (a) Nitrogen ***            | 18,336.09   | 257.78     | 15,405.30 | 352.89     | −19.02         |
| (b) Phosphate ***           | 1154.01     | 26.72      | 870.42    | 49.75      | −32.58         |
| (c) Potassium               | 22.55       | 3.81       | 24.96     | 5.90       | 9.66           |
| 5. Chemicals                |             |            |           |            |                |
| (a) Herbicides              | 382.68      | 4.84       | 376.13    | 7.11       | −1.74          |
| (b) İnsektisit *            | 210.01      | 1.33       | 207.15    | 0.98       | −1.38          |
| (c) Defoliant               | 116.62      | 0.63       | 115.87    | 0.51       | −0.64          |
| 6. Electricity              | 17,897.76   | 1382.50    | 21,708.85 | 2709.51    | 17.56          |
| 7. Water for irrigation *** | 7399.07     | 111.37     | 5915.07   | 205.98     | −25.09         |
| 8. Seed ***                 | 346.41      | 2.86       | 337.57    | 5.25       | −2.62          |
| Total inputs **             | 86,507.62   | 1870.60    | 78,214.57 | 3437.50    | −10.60         |
| <b>B. Output</b>            |             |            |           |            |                |
| 1. Cotton grain yield ***   | 62,537.63   | 473.37     | 56,024.03 | 880.58     | −11.63         |
| Total output                | 62,537.63   | 473.37     | 56,024.03 | 880.58     | −11.63         |

\*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , \*  $p < 0.10$ .

#### 4. Conclusions

As a result of this study, it is seen that cotton farming requires high energy use (83,869.49 MJ ha<sup>-1</sup>), and most of the energy used is non-renewable energy, such as diesel fuel, electricity, chemicals, fertilizers, and machinery. In the research area, the energy use efficiency in cotton farming was found to be 0.87. According to economic efficiency findings, inefficient cotton farms should reduce their cost of production by approximately 52% to reach the level of cotton farms producing at the minimum cost input composition. Cotton farms generate 43% more costs than the minimum cost input composition. The technical efficiency coefficient was determined to be 0.838 on average.

Some suggestions have been presented to save energy in cotton production and to increase the efficiency of enterprises: (1) efforts to improve the energy use of cotton production in the surveyed area should focus on machinery, electricity, and nitrogen; (2) regarding water management, the wild irrigation method should be quit as soon as possible, and pressure irrigation methods should be selected; (3) the amount of fertilizer to be applied to the field should be determined by soil analysis.

This study provides researchers and relevant stakeholders with valuable data revealing the energy use in cotton production of Türkiye, one of the world's largest cotton-producing countries. This study was carried out in three different regions of Türkiye. However, climatic conditions, soil characteristics, farmers' sociodemographic characteristics, and business management structures differ between regions. Therefore, in future similar studies, it is recommended to examine the energy consumption of the regions separately to reveal the regional differences more clearly.

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