

# Effects of grafted seedlings on energy indices and greenhouse gas emissions in watermelon cultivation

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**Abstract:** This study was carried out to analyze and compare energy indices and greenhouse gas (GHG) emissions of grafted and non-grafted watermelon production over three years (2021-2023). Initially, grafted and non-grafted seedlings, which had been previously cultivated in a greenhouse, were manually transplanted onto six plots (with each type allocated to three plots). Energy consumption, watermelon fruit production (Kg ha<sup>-1</sup>), energy indices, and GHG emissions were measured and calculated on each plot. The results indicated no significant difference in average energy consumption between grafted and non-grafted watermelon cultivation. However, there was a very significant difference in their energy indices ( $p < 0.01$ ). energy ratio, energy productivity, specific energy, and net energy gain for non-grafted watermelon were 2.88, 1.52 Kg MJ<sup>-1</sup>, 0.66 MJ Kg<sup>-1</sup>, and 51,551.41 MJ ha<sup>-1</sup>, respectively. For grafted watermelon, these values were 3.65, 1.92 Kg MJ<sup>-1</sup>, 0.52 MJ Kg<sup>-1</sup>, and 72,237.01 MJ ha<sup>-1</sup>, respectively. GHG emissions for grafted and non-grafted watermelon production were 1480.32 and 1395.82 KgCO<sub>2</sub>eq ha<sup>-1</sup>, respectively. But the yield of grafted watermelon increased by 26.1%, then Grafting of watermelon seedlings reduced energy consumption and GHG emissions for one kg watermelon production by 26.3% and 15.15%, respectively.

**Keywords:** Energy productivity, grafted seedling, Sugar Baby, rootstocks of Shintozwa, splice grafting method.

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## 1 Introduction

With the growing global population, the need for increased food production demands greater energy input in agriculture, both directly for field operations and indirectly for input production and transport (Food and agriculture organization of the united nations [FAO], 2018). However, while energy resources are essential for crop production, they can also contribute to environmental pollution (Nabavi-Pelesaraei et al., 2016). Agriculture accounts for

approximately 17% of global greenhouse gas (GHG) emissions (Reddington, 2022). These emissions result from various sources, including machinery, diesel fuel, chemical fertilizers, pesticides, and electricity, with a significant portion linked to chemical inputs (Nabavi-Pelesaraei et al., 2016; Younesi Alamooti and Sedaghat Hosseini, 2014). GHG emissions exacerbate global warming and air pollution, posing risks to public health and ecosystems (Nguyen and Gheewala, 2008).

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In 2016, Iran was the world's second-largest watermelon producer, after China, with a production exceeding 4 million tons. However, due to climate change, ecosystem shifts, and water resource constraints, production declined to 1.2 million tons by 2021 (FAO, 2023).

Energy analysis can assess the impact of various inputs on energy consumption in crop production. In some cases, reducing the consumption of certain inputs can improve energy productivity indices (Fluck and Baird, 1982; Panesar and Fluck, 1993; Clements et al., 1995). For instance, while farms with 12% full irrigation experienced a reduction in crop yield, the energy indices of reduced irrigation fields were more favorable compared to fully irrigated fields (Moradi et al., 2015). In other scenarios, using renewable energy sources is the optimal solution for enhancing energy indices and reducing GHG emissions (Nabavi-Pelesaraei et al., 2016; Safa and Samarasinghe, 2012).

Therefore, energy-efficient practices in agricultural operations are crucial (Sedaghat Hosseini et al., 2014; Nabavi-Pelesaraei et al., 2016). Grafted watermelon cultivation is expanding as an energy-efficient alternative technology with numerous advantages (Miguel et al., 2004; Kubota et al., 2008). However, watermelon grafting faces challenges such as high energy and costs, survival rates, and grafting automation (Devi et al., 2020; Sedaghat et al., 2025). Energy consumption in grafted seedling production can be reduced by adopting technologies like LED-equipped vertical systems (LVS) instead of conventional tunnel systems (CTS) for seedling cultivation (Moosavi-Nezhad et al., 2022).

Although several studies have examined the benefits of grafted crops, there is limited research on energy indices and GHG emissions in grafted watermelon production. The effects of grafting on energy indices and GHG emissions in horticultural crops, especially watermelon, remain unclear. Therefore, more studies are needed to understand the impact of grafting on the energy indices of

agricultural production systems. This study aims to determine and compare energy indices and GHG emissions in grafted and non-grafted watermelon production.

## 2 Material and methods

To calculate and analyze the energy indices and GHG emissions associated with grafted and non-grafted watermelon production, an experiment was conducted at the research farm of the Imam Khomeini Higher Education Centre, located in Alborz Province, Iran.

### 2.1 Experimental site

The experiment was carried out over six plots, each covering 2,100 m<sup>2</sup> (70 × 30 meters). Grafted watermelon seedlings were planted in early spring in three plots, while non-grafted seedlings were planted in the remaining three plots. The necessary cultivation operations for both grafted and non-grafted watermelons were performed on these plots. In Karaj, the summers are hot, arid, and clear and the winters are very cold, snowy, and mostly clear. The soil characteristics of the plots were loamy texture, Electrical conductivity (EC) 4.78, pH 7.76, saturated moisture content 42.61%, organic matter content 1.93%, phosphorus content 68 ppm, potassium 577 ppm, and free nitrogen content 57.79 kg ha<sup>-1</sup>. The previous crop grown was melon.

Input quantities and watermelon yields were measured separately for each plot. The experiment was repeated for three consecutive years, with the data averaged for further analysis.

### 2.2 Watermelon production operations

Since the required inputs (such as fertilizers, pesticides, farmyard manure, water, etc.) differ in grafted and non-grafted watermelon cultivation, in this study, the amount of inputs used was applied in the experimental plots based on the available instructions for each of them separately and according to the following explanations.

#### 2.2.1 Seedling production

In this study, previously prepared grafted and non-grafted watermelon seedlings were used. The

seedlings had been raised in a greenhouse adjacent to the experimental plots. ‘Sugar Baby’ watermelon was grafted onto hybrid rootstocks of ‘Shintozwa’ (*Cucurbita maxima* × *Cucurbita moschata*) using the splice grafting technique. All seedlings were grown and maintained in the greenhouse (38 days duration) until ready for transplanting. The necessary seedlings for this study were prepared annually, before being transplanted to the field, according to the methodology outlined by Sedaghat Hosseini et al. (2025).

### 2.2.2 Tillage and soil preparation

At the end of winter, farmyard manure was manually applied to both grafted and non-grafted watermelon plots at rates of 9 tons ha<sup>-1</sup> and 26 tons ha<sup>-1</sup>, respectively, in accordance with established local practices. After a few days, tillage operations, including chisel and rotary plowing, were performed when soil moisture was suitable. The plant beds were then prepared using bed-shaper-mulcher equipment, with a width of 2.5 meters. Beds were covered with plastic mulch, and drip irrigation tapes were placed under the plastic next to the plant rows. All operations were conducted uniformly across the plots. Fuel consumption (liters), operation duration (seconds), human labour (person-hours, including the

tractor operator), mulch plastic (kg), and drip irrigation tapes (kg) were measured separately for each operation and plot. The fuel used for each operation was measured by refilling the tractor's tank before and after each operation. Data were then converted to a per-hectare basis.

### 2.2.3 Transplanting

Grafted seedlings generally demonstrate greater root and stem vigor compared to non-grafted plants, which enables growers to reduce planting density. Accordingly, in line with conventional horticultural practices, the planting density for grafted seedlings was set at half the density used for non-grafted plants (Lee et al., 2010; Davis et al., 2008). Consequently, the number of grafted seedlings was set at 4,000 plants ha<sup>-1</sup>, while non-grafted seedlings were planted at 8,000 plants ha<sup>-1</sup>. The plant beds had a width of 2.5 meters, with a 5-meter row spacing for grafted seedlings and a 2.5-meter spacing for non-grafted ones (Figure 1). Seedlings were planted at 50 cm intervals within the rows. The plastic mulch was cut using a circular blade, and small holes were dug for each seedling, which were then manually transplanted. Inputs such as human labour and seedlings were recorded.

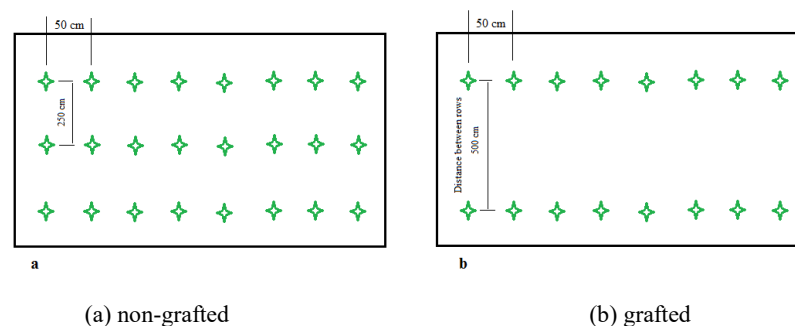


Figure 1 Distances between plants in non-grafted and grafted watermelon plots

### 2.2.4 Irrigation

Immediately after planting, the plots were irrigated. Grafted plants required nearly half the water of non-grafted plants. Irrigation intervals were adjusted based on weather conditions and soil moisture content, but typically, non-grafted plants were irrigated every two days, while grafted plants were irrigated every five days. Water usage was

measured with a volumetric flow meter. Data on irrigation dates, duration, and required human labour (person-hours) were recorded to calculate energy consumption.

### 2.2.5 Fertilizer application

The type and amount of chemical fertilizer applied in watermelon production have a significant impact on overall energy consumption. Chemical

fertilizers, particularly nitrogen-based types, generally account for a substantial portion of total input energy due to their energy-intensive manufacturing processes (Singh et al., 2002; Mohammadi and Omid, 2010). Increasing the application rate of such fertilizers tends to elevate the total energy input per hectare, often without a proportional increase in yield, leading to reduced energy use efficiency (Hatirli et al., 2006). Conversely, optimizing fertilizer types and reducing excessive amounts—by using site-specific nutrient management or integrating organic inputs—not only improves energy productivity but also enhances environmental sustainability (Safa and Samarasinghe, 2011). Thus, rational management of fertilizer use is essential to minimize energy consumption while maintaining high yields in watermelon production.

Chemical fertilizers were applied via fertigation (dissolved in irrigation water). To manage water and fertilizer consumption, separate irrigation and fertilizer injection systems were established for grafted and non-grafted watermelon plots. The type

and quantity of fertilizers used were recorded to determine the required energy.

#### 2.2.6 Spraying

Spraying was performed twice before the watermelon stems reached two meters in length. Fuel consumption, pesticide type and amount, and human labour were recorded.

#### 2.2.7 Harvesting

Harvesting was performed manually, and the human labour required (person-hours) was recorded.

### 2.3 Energy consumption

Energy inputs and outputs for watermelon production in the experimental plots were calculated separately. Inputs included human labour, machinery, diesel fuel, farmyard manure, biocides, fertilizers, plastic, electricity, water, and seedlings, while the output was the watermelon yield. All inputs and outputs were converted to energy (MJ ha<sup>-1</sup>) based on data from Table 1, and averages were calculated across the three years.

**Table 1 Energy equivalent of agricultural inputs and output**

Type of energy	unit	Energy equivalent (MJ unit <sup>-1</sup> )	Reference
Human labour	h	1.96	(Singh and Mittal, 1992)
Machinery	h	62.7	(Rostami et al., 2018)
Diesel fuel	lit	56.31	(Nabavi-Pelesaraei et al., 2014a)
Natural gas	m <sup>3</sup>	49.5	(Kitani, 1999)
Farmyard manure	Ton	7.9	(Ozkan et al., 2004)
Biocide			
Insecticide (OMITE)	Kg	115	(Kitani, 1999)
Fungicide (Thiophanate methyl and Ridomil MZ)	Kg	295	(Kitani, 1999)
Fertilizers			
Energy inputs			
Nitrogen(CO(NH <sub>2</sub> ) <sub>2</sub> )	Kg	66.14	(Nabavi-Pelesaraei et al., 2014a)
Phosphate (P <sub>2</sub> O <sub>5</sub> )	Kg	12.44	(Nabavi-Pelesaraei et al., 2014a)
Potassium (K <sub>2</sub> O)	Kg	11.15	(Nabavi-Pelesaraei et al., 2014a)
Calcium (Ca(NO <sub>3</sub> ) <sub>2</sub> )	Kg	8.8	(Moghimi et al., 2014)
Chemicals	Kg	120	(Namdari, 2011)
Microelements	Kg	120	(Rostami et al., 2018)
Plastic (Mulche)	Kg	11.9	(Azizpanah et al., 2020)
Grafted seedling	plant	2.75	(Sedaghat Hosseini et al., 2025)
Non-grafted seedling	plant	0.42	(Sedaghat Hosseini et al., 2025)
Electricity	Kw.h	11.93	(Ozkan et al., 2004)
Water for irrigation	m <sup>3</sup>	1.02	(Moosavi-Nezhad et al., 2022)
Energy output			
Watermelon	Kg	1.9	(Canakci et al., 2005)

### 2.4 Energy indices

Energy indices, including energy ratio, energy productivity, net energy gain, and specific energy,

were calculated using Equations 1-4 (Kitani, 1999).

$$E_R = \frac{E_O}{E_I} \quad (1)$$

Where,

$E_R$  is energy ratio (efficiency);

$E_O$  is total energy output (MJ ha<sup>-1</sup>);

$E_I$  is total energy input (MJ ha<sup>-1</sup>).

$$E_P = \frac{Y}{E_I} \quad (2)$$

Where,

$E_P$  is energy productivity (Kg MJ<sup>-1</sup>);

$Y$  is watermelon yield (Kg ha<sup>-1</sup>);

$E_I$  is total energy input (MJ ha<sup>-1</sup>).

$$NE_g = E_O - E_I \quad (3)$$

Where,  $NE_g$  is net energy gain (MJ ha<sup>-1</sup>),  $E_O$  is total energy output (MJ ha<sup>-1</sup>), and  $E_I$  is total input energy (MJ ha<sup>-1</sup>).

$$E_S = \frac{E_I}{Y} \quad (4)$$

Where,

$E_S$  is specific energy (MJ Kg<sup>-1</sup>);

$Y$  is yield (Kg ha<sup>-1</sup>);

$E_I$  is total energy input (MJ ha<sup>-1</sup>).

Energy resources were categorized as either direct

(DE) or indirect (IDE). Direct energy included resources directly used in agricultural operations, such as human labour, diesel fuel, and electricity. Indirect energy encompasses the energy used to produce and transport inputs, including machinery, farmyard manure, biocides, fertilizers, plastic, and seedlings. Additionally, energy was classified as renewable (RE) or non-renewable (NRE). Renewable energy included human labour, farmyard manure, and seedlings, while non-renewable energy included machinery, diesel fuel, biocides, fertilizers, plastic, and electricity. The contribution of each energy type to watermelon production was calculated.

## 2.5 GHG emissions

The share of renewable energy was correlated with reduced negative environmental impacts. To compare the pollution from the two watermelon production methods, GHG emissions were measured using the CO<sub>2</sub> emission coefficients of agricultural inputs (Table 2).

**Table 2 GHG emission coefficients of watermelon production inputs**

inputs	unit	GHG Coefficient (Kg CO <sub>2eq</sub> Unit <sup>-1</sup> )	Reference
Human labour	h	0.001	(Pishgar-Komleh et al., 2012)
Machinery	MJ	0.071	(Dyer and Desjardins, 2006)
Diesel fuel	Lit	2.76	(Dyer and Desjardins, 2006)
Biocide (insecticide and fungicide)	Kg	5.1	(Lal, 2004)
Electricity	KW.hr	0.608	(Nabavi-Pelesaraei et al., 2014b)
Phosphate (P <sub>2</sub> O <sub>5</sub> )	Kg	0.2	(Lal, 2004)
Nitrogen (CO(NH <sub>2</sub> ) <sub>2</sub> )	Kg	1.3	(Lal, 2004)
Potassium (K <sub>2</sub> O)	Kg	0.2	(Lal, 2004)
Calcium (Ca(NO <sub>3</sub> ) <sub>2</sub> )	Kg	2.02	(Liu et al., 2014)
Chemicals	Kg	3.28	(Chen et al., 2019)
Farmyard manure	Ton	0.005	(Ekinci et al., 2019)
Plastic	Kg	2.093	(Sinha and Kutnar, 2012)
Grafted seedling	plant	0.133	(Sedaghat Hosseini et al., 2025)
Non-grafted seedling	plant	0.022	(Sedaghat Hosseini et al., 2025)

The three-year average data were converted to kg CO<sub>2</sub> per kg of watermelon produced.

## 2.6 Data analyzing

The experimental data (three-year averages) were analysed using SPSS 26 software. The T-test was used to compare the average energy indices and GHG emissions in grafted and non-grafted watermelon production.

## 3 Results and discussion

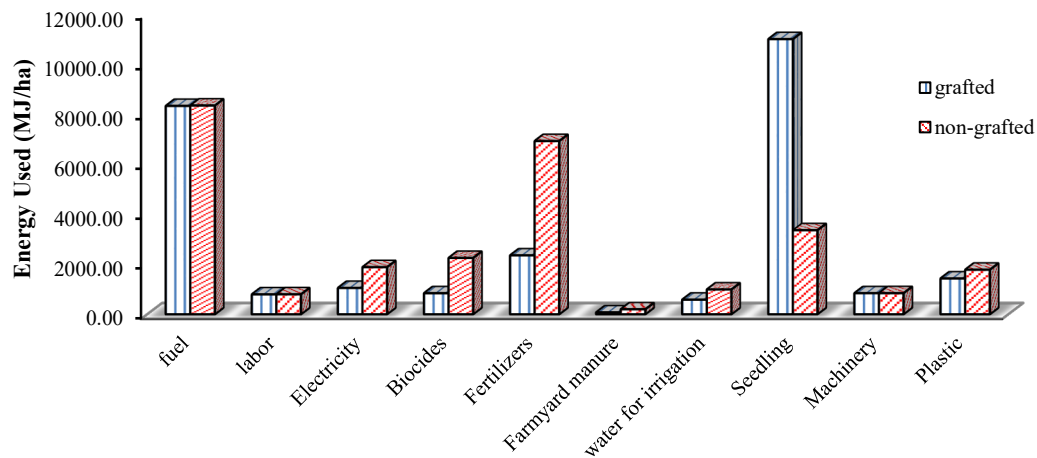
### 3.1 Energy indices

While the energy consumption for grafted

watermelon seedling production (2.75 MJ plant<sup>-1</sup>) was higher than for non-grafted seedlings (0.42 MJ plant<sup>-1</sup>), the total energy consumption in non-grafted watermelon production (27,370.16 MJ ha<sup>-1</sup>) was slightly higher than in grafted production (27,289.43 MJ ha<sup>-1</sup>). Since the inputs required for grafted watermelon production were lower than for non-grafted watermelon, most of the energy input (human power, machinery, diesel fuel, pesticides, electricity, fertilizers, manure, and plastic) was equal to or lower for grafted watermelon production (Figure 2). While in the seedling production stage, the use of more

inputs in the healing and adaptation stage, as well as the cultivation of a larger number of seedlings (both rootstocks and scions) in the production of grafted seedlings, are the main reasons for increased energy

consumption and greenhouse gas emissions compared to non-grafted seedlings (Sedaghat Hosseini et al. 2025).



### Energy Resources

Figure 2 Comparison of energy inputs of grafted and non-grafted watermelon production (MJ ha<sup>-1</sup>)

Since the stages of grafted and non-grafted watermelon cultivation were almost the same, the difference in energy consumption of diesel fuel, machinery, and labor inputs in these two methods was insignificant. Energy consumption of electricity, biocides, fertilizers, farmyard manure, and water for irrigation in grafted watermelons was significantly reduced. This is because grafted plants are more resistant to diseases, drought stress, and nutrient deficiencies compared to non-grafted plants, as the results of previous studies confirm it (Rouphael et al., 2008; Colla et al., 2010; Colla et al., 2011; Thies et

al., 2010; Abdelhafidh et al., 2019; Miguel et al., 2004). On the other hand, the energy consumed in producing grafted seedlings is many times higher than that of non-grafted seedlings (Sedaghat Hosseini et al., 2025), which has made the difference in total energy consumption between grafted and non-grafted watermelons insignificant. Since the yield of the grafted plant was higher than that of the non-grafted one (Ricárdez-Salinasa et al., 2010; Abdelhafidh et al., 2019; Cohen et al., 2012), the difference in energy production between grafted and non-grafted watermelons became significant ( $p < 0.01$ ) (Table 3).

Table 3 Energy input-output and indices in grafted and non-grafted watermelon production

Type of energy	Unit	Grafted watermelon	Non-Grafted watermelon
Energy inputs	Diesel fuel (MJ ha <sup>-1</sup> )	8328.92 <sup>a</sup>	8344.85 <sup>a</sup>
	Human labor (MJ ha <sup>-1</sup> )	793.78 <sup>a</sup>	796.25 <sup>a</sup>
	Electricity (MJ ha <sup>-1</sup> )	1050.05 <sup>a</sup>	1882.6 <sup>b</sup>
	Biocides (MJ ha <sup>-1</sup> )	840.00 <sup>a</sup>	2252 <sup>b</sup>
	Fertilizers (MJ ha <sup>-1</sup> )	2352.85 <sup>a</sup>	6925.2 <sup>b</sup>
	Farmyard manure (MJ ha <sup>-1</sup> )	72.1 <sup>a</sup>	197.84 <sup>b</sup>
	seedlings (MJ ha <sup>-1</sup> )	11000.00 <sup>b</sup>	3360.00 <sup>a</sup>
	Machinery (MJ ha <sup>-1</sup> )	840.40 <sup>a</sup>	842.0 <sup>a</sup>
	water for irrigation (MJ ha <sup>-1</sup> )	582.00 <sup>a</sup>	989.40 <sup>b</sup>
	Total energy input (MJ ha <sup>-1</sup> )	27289.43 <sup>a</sup>	27370.16 <sup>a</sup>
output	Watermelon (Kg ha <sup>-1</sup> )	52382.33 <sup>b</sup>	41537.67 <sup>a</sup>
	Energy output (MJ ha <sup>-1</sup> )	99526.43 <sup>b</sup>	78921.57 <sup>a</sup>
Energy indices	energy ratio	3.65 <sup>b</sup>	2.88 <sup>a</sup>
	energy productivity (Kg MJ <sup>-1</sup> )	1.92 <sup>b</sup>	1.52 <sup>a</sup>
	net energy gain (MJ ha <sup>-1</sup> )	72237.01 <sup>b</sup>	51551.41 <sup>a</sup>
	Specific energy (MJ Kg <sup>-1</sup> )	0.52 <sup>a</sup>	0.66 <sup>b</sup>

Note: Values marked with different letters (a and b), show a significant difference ( $P < 0.01$ ) between it means of two methods (grafted and non-grafted) and item only with a letter (a) there is no significant difference.

Although grafted watermelon production reduced energy consumption of electricity, biocides, fertilizers, farmyard manure, plastic, and water for irrigation, the increase in energy consumption during the grafting stage led to a negligible difference in total energy input between the two methods. Grafted watermelon production reduced energy consumption by 0.29% compared to non-grafted watermelon, but this reduction was not statistically significant. However, grafted watermelon achieved a 26.10% higher yield than non-grafted, leading to improved energy productivity ( $1.92 \text{ kg MJ}^{-1}$ ) by 26.49% compared to non-grafted watermelon ( $1.52 \text{ kg MJ}^{-1}$ ). All energy indices for grafted watermelon were improved over

non-grafted production. Total energy consumption in both methods of watermelon production was lower than the results of most previous studies reviewed (Rostami et al., 2018; Nabavi-Pelesaraei et al., 2014a; Namdari, 2011; Azizpanah et al., 2020; Canakci et al., 2005).

The primary energy-consuming inputs in grafted watermelon production were seedlings (40.31%), diesel fuel (30.52%), fertilizers (8.62%), plastic (5.24%), and electricity (3.85%) (Fig 3-a). For non-grafted watermelon production, the largest inputs were diesel fuel (30.49%), fertilizers (25.30%), seedlings (12.28%), biocides (8.23%), and electricity (6.88%) (Figure 3-b).

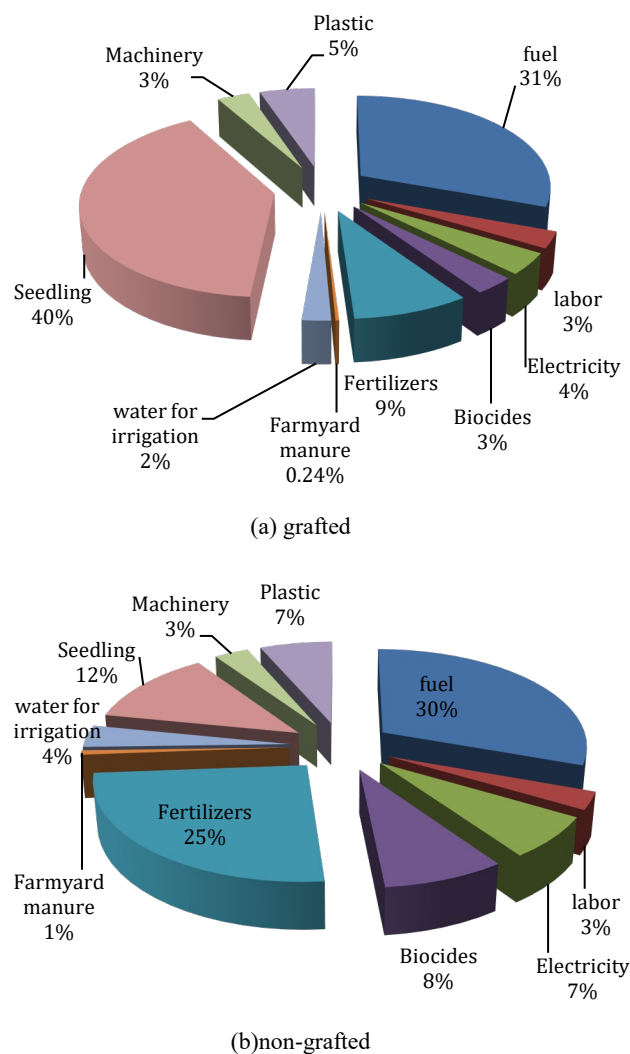


Figure 3 Resources of energy consumption in the grafted and non-grafted watermelon production

The share of seedling energy consumption increased from 12.28% in non-grafted to 40.31% in grafted watermelon production. This increase of

28.03% (despite the reduction of all other energy inputs) made the difference in the averages of the total energy consumption in the grafted and non-

grafted seedlings production meaningless. Therefore, the use of methods such as vertical cultivation that can reduce the consumed energy for grafted seedlings production has a great effect on increasing the energy productivity of grafted watermelon (Moosavi-Nezhad et al., 2022).

Although the total energy input for grafted watermelon production was lower, the share of renewable energy increased from 15.91% in non-grafted production to 43.48% in grafted production (Figure 4).

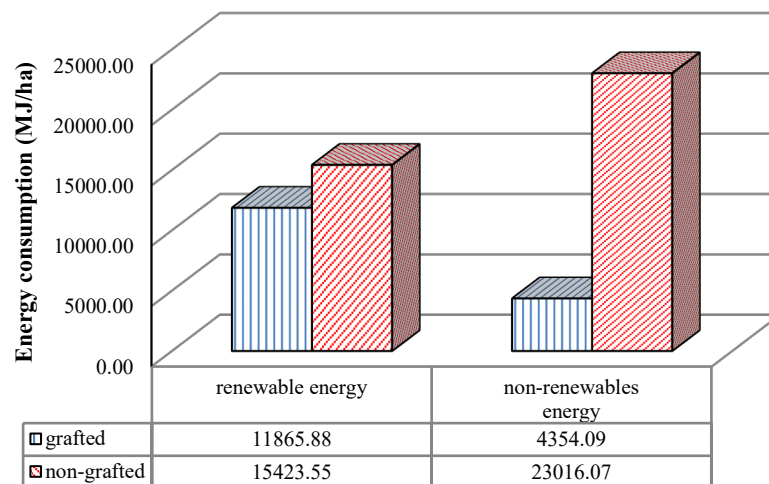


Figure 4 Contribution of renewable and non-renewable energies in the grafted and non-grafted watermelon production ( $\text{MJ ha}^{-1}$ )

**Table 4 GHG emissions of grafted and non-grafted watermelon production**

Inputs	GHG emissions ( $\text{kgCO}_2\text{eq ha}^{-1}$ )		Difference
	Grafted watermelon	Non-grafted watermelon	
Human labour	0.41	0.41	0.00
Machinery	59.67	59.78	0.11
Diesel fuel	408.24	409.02	0.78
Biocides	35.70	96.90	61.2
Electricity	183.62	317.95	134.33
Phosphate	1.32	3.96	2.64
Nitrogen	5.46	16.38	10.92
Potassium	1.68	5.04	3.36
Plastic	251.16	313.95	62.79
Farmyard manure	0.05	0.13	0.08
seedling	533.03	172.31	360.72
Total	1480.32	1395.82	84.5

Drip irrigation tapes application increased efficiency of irrigation (Ortiz-Diaz et al., 2024). This is that the energy of electricity has significantly decreased, when compared to the results of previous studies. Also, the weeding operation eliminated due to the use of plastic mulch. However, these (drip irrigation tape and plastic mulch application) reduced energy consumption and increased energy productivity.

Because the fertilizer was applied with the irrigation system (fertigation), the efficiency of the fertilizer increased in this study. The consumption of chemical fertilizers was significantly reduced compared to the results of other studies (Moghimi et

al., 2014; Nabavi-Pelesaraei et al., 2016; Namdari, 2011). This is due to two reasons: firstly, the separate fertilizing operation has been removed, and secondly, due to the high efficiency, then the amount of fertilizer consumed has been reduced.

Even though the average total energy consumption for grafted and non-grafted watermelon production was almost the same, the increase of 26.1% in the yield of grafted watermelon led to the improvement of energy ratio, energy productivity and specific energy indices by 26.3% and specific energy index by 40.12%. The energy productivity index in this study was better than the results reported in all previous studies reviewed.

### 3.2 GHG Emissions

GHG emissions in grafted and non-grafted watermelon production was 1480.32 and 1395.82 (kgCO<sub>2</sub>eq ha<sup>-1</sup>), respectively (Table 4). GHG emissions in grafted watermelon production were 6.05% higher than in non-grafted watermelon.

While the GHG emissions of most grafted watermelon production inputs were lower than the non-grafted ones, only the GHG emissions of the grafted seedling inputs were higher than non-grafted ones. In general, the GHG emissions for grafted watermelon production were 6.05% higher than non-grafted type, but their difference was not significant.

The GHG emissions per one kilogram of grafted and non-grafted watermelon were 0.028 and 0.033

kgCO<sub>2</sub>eq Kg<sup>-1</sup>, respectively. In the grafted watermelon production, only the GHG emissions from seedling production are more than non-grafted one. However, it is more in other inputs of non-grafted watermelon production.

The inputs with the largest share of GHG emissions were diesel, plastic, seedling, and electricity (Figure 5).

GHG emissions from most of the inputs (human labour, machinery, diesel, biocides, electricity, fertilizers and plastic) for non-grafted watermelon production were more than grafted one (Figure 6). But GHG emissions from grafted seedling were higher than non-grafted one.

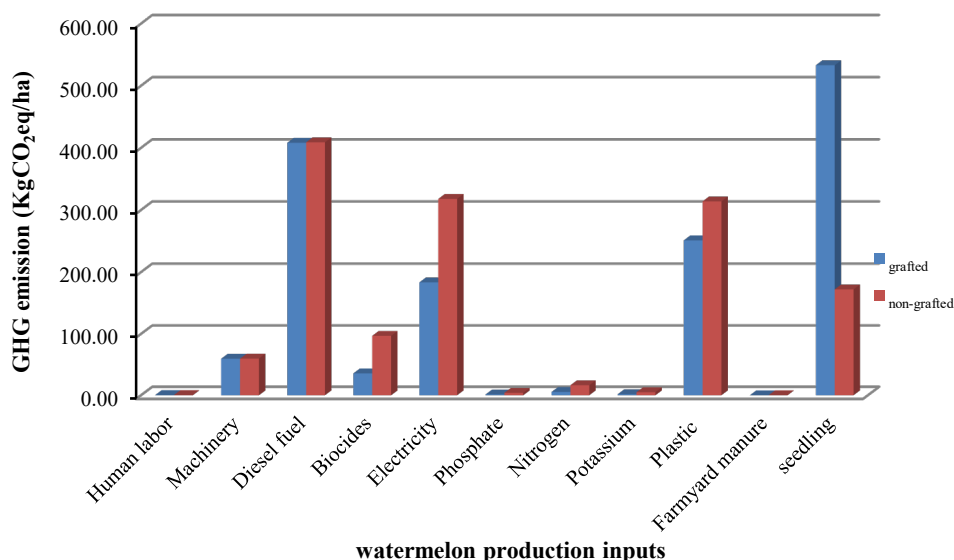
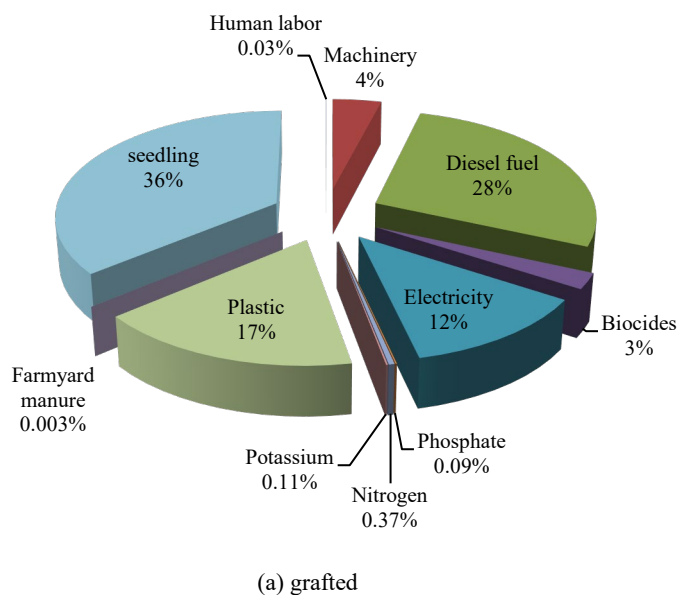


Figure 5 GHG emissions of grafted and non-grafted watermelon production (kgCO<sub>2</sub>eq ha<sup>-1</sup>)



(a) grafted

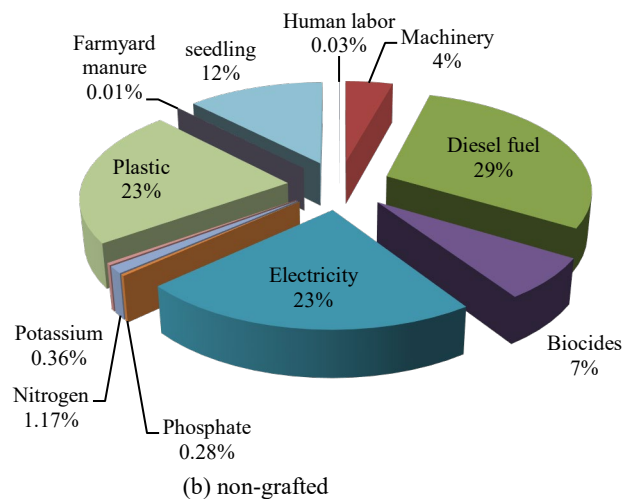


Figure 6 Resources of GHG emissions for grafted, and non-grafted watermelon production

Although the share of renewable energy in watermelon production increased from 15.91% in the non-grafted type to 43.48% in the grafted type, its GHG emission also increased from 1395.82 to 1480.32 kg CO<sub>2</sub>eq ha<sup>-1</sup>. While renewable energy resources have a significant negative impact on CO<sub>2</sub> emissions (Moghimi et al., 2014). The reason for this increase in the share of plastic in the grafted seedlings production is that the emission of GHG increased from 0.022 to 0.133 kg CO<sub>2</sub>eq plant<sup>-1</sup>.

In the grafted seedlings production, due to the additional grafting stage, more inputs were used, and it is also necessary to cultivate two seedlings (rootstock and scion) for each grafted seedling. Therefore, energy consumption and GHG emissions in the grafted watermelon production were more than non-grafted ones.

Generally, the inputs that mainly contribute to GHG emissions from watermelon production include diesel fuel, electricity, seedlings, and plastic. Although the GHG emission per a hectare of this study was almost similar to other studies, due to the higher yield, the GHG emission per kilogram of watermelon production was slightly lower than the results of other studies (Nabavi-Pelesaraei et al., 2016; Azizpanah et al., 2020; Nabavi-Pelesaraei et al., 2014b).

The results of this study indicated that, overall, grafting watermelons improves energy efficiency indices and enhances their effectiveness.

Consequently, it is essential to reduce energy consumption—particularly that of non-renewable sources—during the seedling cultivation stage.

## 5 Conclusion

The results of this study are summarized as follows.

Grafted seedlings reduced the energy consumption in watermelon production slightly (0.29%) compared to the non-grafted type, but this reduction was no significant.

Grafted seedlings improved the energy indices by 26.3%-40.12% compared to the non-grafted type, in watermelon production.

Grafted seedlings decreased GHG emissions by 15.15% compared to the non-grafted type, for one kilogram watermelon production.

Grafted seedling production had the largest share in both energy consumption (40.31%) and GHG emissions (36.01%) in grafted watermelon cultivation.

Reducing energy consumption, especially non-renewable resources (such as plastic) in the grafted seedlings producing stage can improve the effects of grafted seedlings application on energy indices and greenhouse gas emissions.

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