# Assessment of the sustainability of the traditional and mechanized cultivation process with an exergy-based approach

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**Research Article**

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**Abstract**

Regarding the high consumption of allium vegetables such as onion and green onion in the daily food basket of families, it is important to study the sustainability of their agricultural system. Thus, a thermodynamic analysis was carried out to assess the sustainability of the cultivation method management using an exergy-based approach. Onions and green onions were evaluated for mechanized cultivation and for traditional cultivation, respectively. The use of renewable energy in the cultivation system was proposed in the numerical method. The sustainability index and exergetic improvement potential were calculated. Moreover, and the improvement of CDP and RI factors was investigated based on the CExC approach. The results indicated energy consumption of 1 ton of onion production was 2.5 times that of green onion production. The human labor and electricity as energy-intensive inputs in the process of green onion and onion production, respectively. The GHG emission of 1 ton of onion production was obtained 3 times that of green onion production. The results showed that the impact of using the new strategy in the agricultural system of green onions is less than onions, due to the high human labor requirement in green onion production, which made the production of green onions even more unsustainable than the production of onions, despite less consumption energy in green onion production.

**Key words:** Sustainability, Onion, Green Onion, Thermodynamic Analysis, Exergy, Traditional and mechanized cultivation

## 1. Introduction

Dincer (Dincer 2002) showed a relationship between energy and exergy with the environment and sustainable development. Energy analysis based on the first law of thermodynamics is a traditional method for estimating various processes of energy conversion, however, it does not provide information on the quantity and mechanism of performance reduction. The second law of thermodynamics examines the energy quality by exergy (Szargut 2005; Hepbasli 2008) and also offers new ideas for improving and stabilizing the system (Dincer 2002; Saidur et al. 2007). The CExC approach can identify the impacts of using different inputs of production on the environment (Szargut

2005). With the help of CExC approach, farmers can improve production productivity. The CExC approach can evaluate the cumulative degree of perfection (CDP) and renewability index (RI) for each stage of the production process and ultimately offers solutions to increase product productivity. Some studies have used this approach for some crop production. The CExC evaluation of tomato production by two methods of greenhouse cultivation and open field showed very high electricity and water consumption in the open field and greenhouse cultivations, respectively (Yildizhan and Taki 2018). A similar study was conducted to optimize strawberry production and showed that the energy required to produce 1 ton of strawberries in the greenhouse cultivation is less than the open field. The CDP values were 0.29 and 0.18 for greenhouse and open field production, respectively. In another study, for potato production, reducing the use of pelletized manure was suggested to increase CDP and reduce $CO_2$ emissions (Yildizhan 2017). Thermodynamic analysis of greenhouse cucumber production showed that when the process of greenhouse cucumber production is done with renewable energy, CDP increased from 0.23 to 0.47, while exergy efficiency and RI indicated growth from 0.18 and -3.32 to 30.30 and -1.09, respectively. Investigation of energy and exergy consumption and $CO_2$ emissions during soybean, sunflower, and olive production showed that reducing diesel consumption by proper farming method or replacing diesel with biodiesel will reduce exergy consumption (Özilgen and Sorgüven 2011).

Epidemiological studies indicated the inverse relationship of consumption of allium vegetables (such as leeks, garlic, onions, green onions, and scallion) with gastric and colon cancer due to their chemical protection. Onions and alum-related products are the most consumed vegetables in the world (Xiao and Parkin 2007). The literature review shows that although allium vegetables have high consumption in the daily food basket of families, the sustainability of their production process has not been studied so far. Therefore, in this research, the sustainability of green onion production as traditional cultivation and onion production as mechanized cultivation are investigated. Also human labor was ignored in the thermodynamic analysis of agricultural products. Therefore, in this study, while considering the human labor, the energy-exergy flow of the cultivation process of two similar plants (onion and green onion) was evaluated. The sustainability index and exergetic improvement potential were also calculated; the improvement of CDP and RI was investigated based on the CExC approach.

## 2. Materials and Methods

Farm data provide important information for a specific farm. Data from several farms can provide more general results. Thermodynamics analysis of farm-level data can test inputs and techniques to evaluate the efficiency of potential inputs and identify the prominent elements with the highest impact on sustainability. In this study, the production process of onions and green onions was investigated. **Table 1** show data for green onion agriculture that were collected from green onion farmer. Data for onion were extracted from the work of Hassanzadeh Aval and Rezvani Moghaddam ( 2013) as presented in **Tabl 2**.

**Table 1** Inputs used to produce 1 ton of green onions

| **Inputs** | **Value (unit per ton)** |
|---|---|
| Human labor (h) | 260.10 |
| Animal work (h) | 2.30 |
| Seed (kg) | 8.97 |
| Nitrogen (kg) | 4.48 |
| Phosphorous (kg) | 4.48 |
| Fungicides (L) | 0.13 |
| Farmyard manure (kg) | 456.74 |

**Table 2** Inputs used to produce 1 ton of onions (Hassanzadeh Aval et al., 2013)

| **Inputs** | **Value (unit per ton)** |
|---|---|
| Human labor (h) | 23.13 |
| Seed (kg) | 0.15 |
| Diesel (L) | 1.73 |
| Nitrogen (kg) | 2.99 |
| Phosphorous (kg) | 2.5 |
| Potassium (kg) | 1.49 |
| Herbicides (L) | 0.03 |
| Insecticides (L) | 0.05 |
| Fungicides (L) | 0.02 |
| Farmyard manure (kg) | 301.80 |
| Electricity (kWh) | 190.03 |
| Irrigation water ($m^3$) | 162.99 |

The production of 1 ton of product can be thermodynamically analyzed by the balance of mass, energy, and exergy (Szargut 2005; Cengel and Boles 2007; Hepbasli 2008):

Mass balance:

$$\sum m_{in} = \sum m_{out} \tag{1}$$

Energy balance:

$$\sum (mh)_{in} - \sum (mh)_{out} = \sum Q_k - W \tag{2}$$

Exergy balance:

$$\sum (mb)_{in} - \sum (mb)_{out} + \sum Q_k \left(1 - \frac{T_0}{T_k}\right) - W = X_{loss} \tag{3}$$

Where m: mass (kg), Q: heat energy, T: temperature (K), h: enthalpy, W: work (MJ), k: heat sources, and b: available exergy flow of the product, which can be calculated from the following equation:

$$b = -T_{0S} = R_u T_0 \sum_i y_i \ln(y_i) \tag{4}$$

In which, s shows the specific entropy, $R_u$ denotes the universal gas constant and $y_i$ represents the molar fraction. The amount of available flow (b) for the crops is described in **Appendix A**.

The performance of the crops production process can be assessed by calculating CDP (Szargut et al. 1987):

$$CDP = \frac{(mb)_{product}}{\sum (mCExC)_{inputs}} \tag{5}$$

where CExC is the exergy of all raw materials and fuels consumed during crop production. **Table 3** shows the thermodynamic coefficients of the inputs used to produce onions and green onions.

The renewability index, which is the exergy deviation from the ideal behavior due to the consumption of non-renewable resources, is calculated as follows (Berthiaume and Bouchard 1999) :

$$RI = \frac{(X_p - W_r)}{X_p} \tag{6}$$

where $X_p$ is the useful work derived from the product and $W_r$ stands for non-renewable resources consumed during the production process.

Depending on the value of RI, the renewability of the production process is determined as follows:

The process is completely renewable, if RI = 1

The process is somewhat renewable, if 0 <RI <1

Production and reconstruction work are equal if RI = 0

The process is non-renewable, if RI <0

Van Gool (1997) proposed a new parameter of exergy called the improvement potential. Improvement potential is commonly used to analyze various processes. This parameter indicates the extent of improvement potential for a system:

$$IP = (1-\varepsilon)\left[Ex_{in} - Ex_{out}\right] \tag{7}$$

where $\varepsilon$ is the exergy efficiency and can be defined as the ratio of total output exergy to input exergy.

$$\varepsilon = \frac{Ex_{useful}}{Ex_{in}} \quad (8)$$

Exergy sustainability is based on exergy analysis and is defined as the relationship between the input exergy and the system exergy losses. This index offers information about the impact of the process on the environment and can be considered as an important parameter of evaluation. The exergy sustainability index can be calculated as follows:

$$SI = \frac{1}{(1-\varepsilon)} \quad (9)$$

**Table 3** Thermodynamic coefficients of inputs

| Inputs | CEnC equivalent | CExC equivalent | $CCO_2E$ equivalent |
|---|---|---|---|
| Human labor | 1.96 MJ $h^{-1}$ (Yaldiz et al., 1993) | 59.06 MJ $h^{-1}$ (Chen et al., 2020) | 0.11 kg $h^{-1}$ (Yan et al., 2014) |
| Animal work | 5.05 MJ $h^{-1}$ (De et al., 2001) | 9.85 MJ $h^{-1}$ calculated based on (Qian et al., 2017 | 0.67 kg $h^{-1}$ (MARASENI et al., 2009) |
| Seed | 1.6 MJ $kg^{-1}$ (Özilgen, 2018) | 3.24 MJ $kg^{-1}$ (Özilgen, 2018) | 0.08 kg $kg^{-1}$ (Özilgen, 2018) |
| Diesel | 47.87 MJ $L^{-1}$ (Cervinka, 1980) | 53.2 MJ $L^{-1}$ (Szargut et al., 1987) | 2.62 kg L (Kawamoto et al., 2019) |
| Electricity | 12 MJ $kWh^{-1}$ (Cervinka, 1980) | 4.17 MJ $MJ^{-1}$ (Szargut et al., 1987) | 0.308 kg $MJ^{-1}$ (Jensen and Arlbjørn, 2014) |
| Irrigation water | 1.02 MJ $m^{-3}$ (Acaroğlu and Acaroglu, 1998) | 2.6 MJ kg (Özilgen, 2018) | 0.09 kg kg (Özilgen, 2018) |
| Nitrogen fertilizer | 78.1 MJ $kg^{-1}$ (Mudahar and Hignett, 1987) | 32.7 MJ $kg^{-1}$ (Özilgen, 2018) | 5.917 kg $kg^{-1}$ (Jensen and Arlbjørn, 2014) |
| Phosphate | 17.4 MJ $kg^{-1}$ (Mudahar and Hignett, 1987) | 7.52 MJ $kg^{-1}$ (Wittmus et al., 1975) | 1.014 kg $kg^{-1}$ (Jensen and Arlbjørn, 2014) |
| Potassium | 13.7 MJ $kg^{-1}$ (Mudahar and Hignett, 1987) | 4.56 MJ $kg^{-1}$ (Pimentel, 1991) | 0.579 kg $kg^{-1}$ (Jensen and Arlbjørn, 2014) |
| Farmyard manure | 0.47 MJ $kg^{-1}$ (Stout, 1990) | 5.33 MJ $kg^{-1}$ (Özilgen, 2018) | 0.0462 kg $kg^{-1}$ (Özilgen, 2018) |
| Insecticides | 184.63 MJ $L^{-1}$ (Pimentel, 1980) | 344 MJ $kg^{-1}$ (Özilgen, 2018) | 5.1 kg $kg^{-1}$ (Özilgen, 2018) |
| Herbicides | 254.45 MJ $L^{-1}$ (Pimentel, 1980) | 368.4 MJ $kg^{-1}$ (Özilgen, 2018) | 6.3 kg $kg^{-1}$ (Özilgen, 2018) |
| Fungicides | 97.00 MJ $L^{-1}$ (Pimentel, 1980) | 256 MJ $kg^{-1}$ (Özilgen, 2018) | 3.9 kg $kg^{-1}$ (Özilgen, 2018) |

## 3. Results and discussion

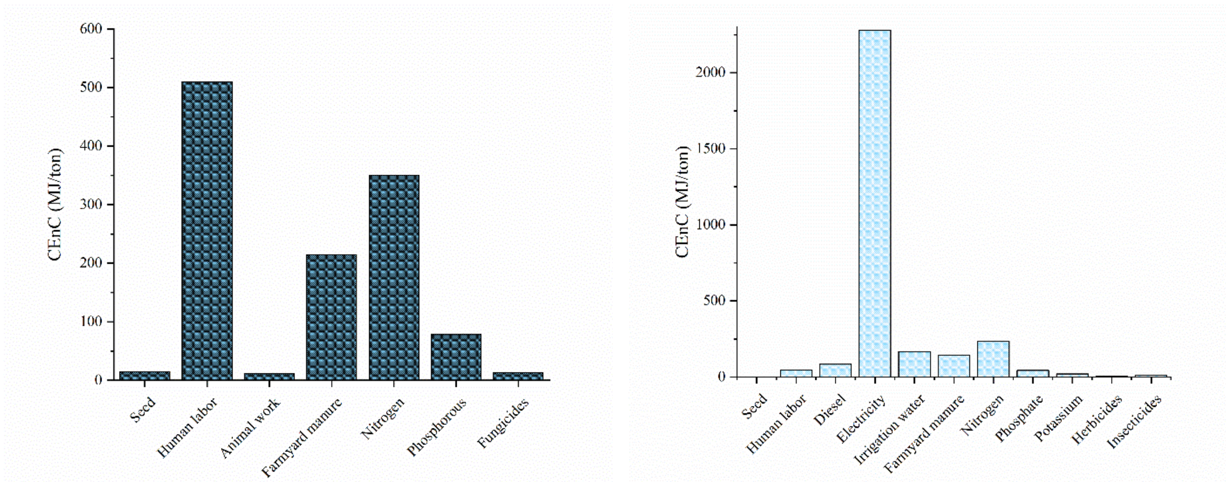
### 3.1 Thermodynamic analysis

In this study, cumulative energy consumption (CEnC), cumulative exergy consumption (CExC), GHG emissions ($CCO_2E$), and renewable indicators (i.e. CDP, RI, exergetic sustainability index, and improvement potential) were thermodynamically estimated for onion and green onion production. Then, the effect of using renewable energy on the farming system of both crops was discussed. The functional unit for calculations was considered as the production of 1 ton of onions and green onion. As no research has addressed onions and green onions, the results of this study were compared with other agricultural products.

The energy consumption of production inputs during the production of 1 ton of onions and green onions is shown in **Figure 1.** The CEnC for each ton of green onion and onion were obtained 1.19 and 3.03 GJ, respectively. As **Figure 1.a** illustrates, in the green onion production system, the largest share of energy consumption is related to human labor, followed by nitrogen and manure. Because green onions production is done on small scale by smallholder farmers, and except for land preparation, which used animal labor, other operations are carried out by the human labor.

In the production of strawberries (Yildizhan 2018), tomatoes (Yildizhan and Taki 2018), and apples (Yildizhan et al. 2021), fertilizers (nitrogen and manure) was reported as the most important energy-intensive input. According to Zand Salimi et al. (2007) on manures, chicken manure had the highest amount of bacteria with high impacts on environmental pollution. Their study, however, showed that cow manure had lower bacterial contamination. Due to its low absorption (organic matter), a higher percentage of bacteria was released. Thus, manure is the source of dangerous pathogenic bacteria that can contaminate soil and surface, and groundwater. Therefore, the use of biofertilizers in sustainable and organic agriculture is highly recommended.

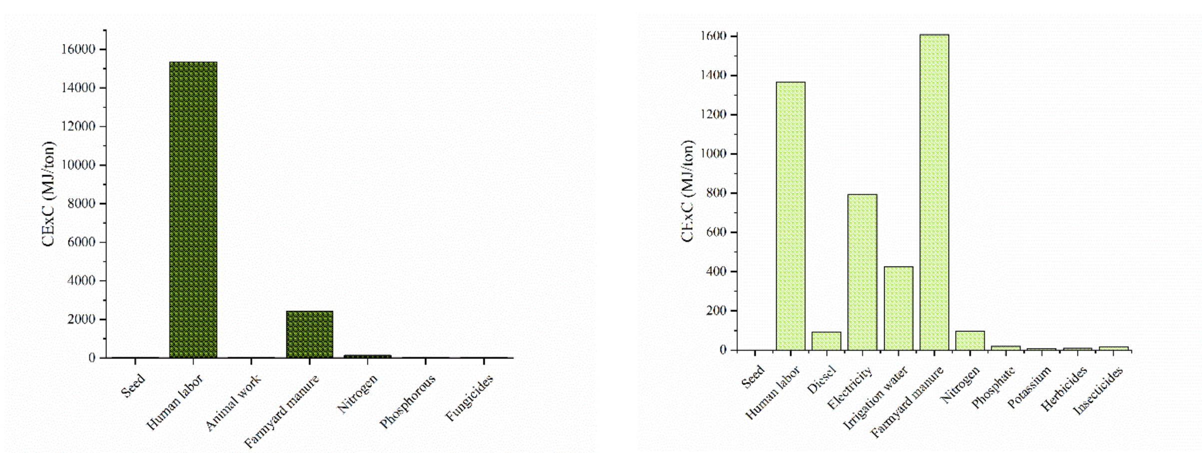
The CEnC of onions production is 2.5 times of green onions. The high energy consumption in the onion production system is due to the high electricity consumption. Electricity consumption accounts for 75.19% of the total energy consumption. All electricity consumption in onion production is related to the irrigation system. Most farmers use electric motors to extract water from deep wells. In addition to tractor fuels and transportation, diesel fuel was used to pump water from some wells. Due to the low groundwater aquifers, high levels of electricity and fuel are needed to exploit water from deep wells. Taki and Yildizhan ( 2018) in cucumber production and Yildizhan and Taki (2019) in wheat production also reported high electricity and diesel consumptions due to the energy-demanding task of water extraction from deep wells.




**(a) Green onion** **(b) Onion**

**Figure 1** CEnC of inputs to produce 1 ton of (a) green onions and (b) onions

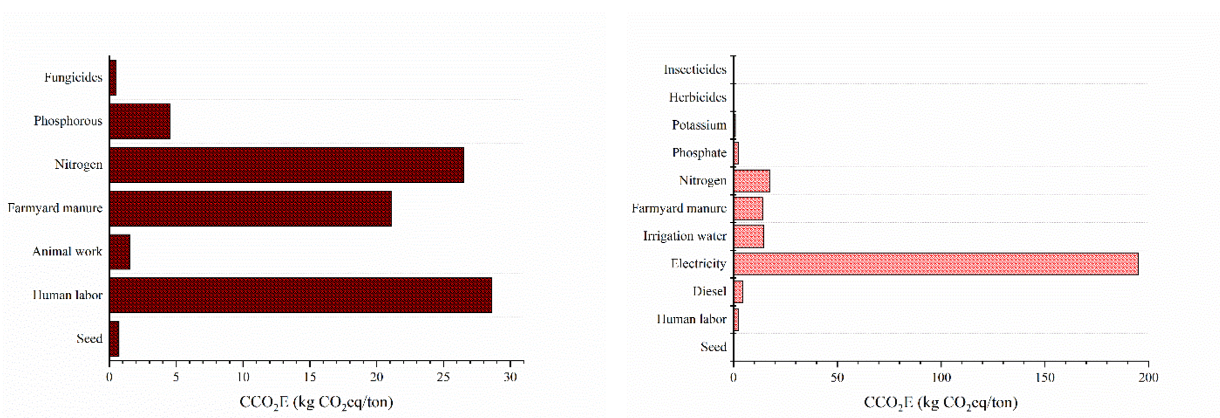
CExC method can be used to evaluate the production process. Reducing CExC can save natural resources for the next generation, as well as control GHG emissions and improve human quality of life. **Figure 2** shows the exergy inputs for the production of 1 ton of onions and green onions. As can be seen, human labor (42.78%) had the largest share in production exergy for green onions and manure (36.23%) had the largest share in production exergy for onions. In onion production, human labor (30.78%) electricity (17.85%) and irrigation water (9.54%) are the next inputs with the largest share in the CExC. The shares of other onion and green onion production inputs in the total exergy were less than 5%. Similar results were obtained for exergy-based inputs in the production of apple (Yildizhan 2018), potatoes (Yildizhan 2017), and tomatoes (Yildizhan and Taki 2018). The manure, electricity, and water were the most widely used exergy inputs in the production process of apple (Yildizhan et al. 2021), potato (Yildizhan 2017), and tomato (Yildizhan and Taki 2018), respectively. Thus, irrigation and fertilization can significantly improve exergy.




**(a) Green onion** **(a) Onion**

**Figure 2** CExC of inputs to produce 1 ton of (a) green onions and (b) onions

In addition to imposing costs on farmers and lower profits, one of the problems of overuse and improper consumption of agricultural inputs is environmental pollution. **Figure 3** shows the GHG emissions from various inputs of the onion and green onion production process. The total emissions to produce 1 ton of onions and green onions were 83.58 and 252.40 kg $CO_2$, respectively. **Figure 3.a** shows that in green onion production, the largest share of GHG emissions is related to human labor and fertilizers (nitrogen and manure). While **Figure3.b** shows that for the production of onions electricity had the largest share in GHG emissions. The $CO_2$ emissions value per ton of onions was 3 times the amount of carbon dioxide emissions per ton of green onions. In the production of open field tomato (Yildizhan and Taki 2018), open field strawberries (Yildizhan 2018), greenhouse strawberries (Yildizhan 2018), greenhouse cucumbers (Taki and Yildizhan 2018), and wet wheat (Yildizhan and Taki 2019), the inputs of irrigation operations- i.e. electricity to extract water from deep wells and irrigation water- were the most important factors in GHG emission. Moreover, due to the high consumption of electricity in the production of greenhouse strawberries, GHG of greenhouse strawberry production was more than open field. Taki and Yildizhan (2018) proposed that an improvement in the irrigation system and changing the structure of the greenhouse can reduce electricity-induced GHG emissions.




**(a) Green onion** **(a) Onion**

**Figure 3** $CCO_2E$ of inputs to produce 1 ton of (a) green onions and (b) onions

### 3.2 Sustainability analysis

In this section, the sustainability indicators of onion and green onion production (improvement potential, exergetic sustainability index, CDP, and RI) were investigated (**Figure 4**).

The CDP was calculated as a criterion for exergy efficiency. This factor can be interpreted as the input/output ratio of the exergy. The output exergy of the product depends on the chemical composition or in other words the nutritional value of the product. High CDP means either a high nutritional value of the product or low total exergy consumption during the production process. Thus, the higher the CDP value, the lower the exergy losses. The CDP was obtained 0.13 for green onions and 0.46 for onions implying that onion production is more environmentally friendly than onion in Iran.

According to Berthiaume and Bouchard (1999), RI is a useful tool for technology and environmental decision-makers. The RI shows the deviation from the ideal behavior due to the use of non-renewable resources. The RI is highly dependent on the limitations of the technology and applied resources. IR was -1.18 and -6.80 for onion and green onion, respectively; emphasizing the non-renewability of onion and green onion production (i.e. repair work is more than production work).

Exergy improvement potential was 1297 and 13728 MJ for onions and green onions, respectively. These values indicate that the green onion production process has a high potential to improve exergy efficiency. At higher exergy efficiencies, the sustainability index is higher and the environmental effects will be less. The sustainability index for onion and green onion production was 1.85 and 1.15, respectively. To reduce the environmental impact, exergy efficiency must be improved. A comparison of the results shows that the improvement potential value of green onion is much higher than that of onion which could be due to the incorrect and excessive use of inputs (especially human labor) in green onion production compared to the onion production. According to Equation (7), the higher the exergy efficiency and the lower the exergy losses, the lower the exergy improvement potential. In other words, the lower the improvement potential, the more efficiently the inputs are used and the better the system performs. In a study by Yildizhan et al. (Yildizhan et al. 2021) on apple production, the improvement potential for apple production was 9232.02MJ. Because human labor was neglected in apple production, the sustainability of apple production cannot be compared with onion and green onion production.

### 3.3 A novel strategy for improving the farming system

Agricultural industrialization has led to an intensification of energy use in agricultural systems with an increase in the use of fertilizers, pesticides, machinery, and irrigation expansion. Increased consumption of inputs and high dependence on agriculture, especially on non-renewable resources, are obvious signs of instability in food production systems. In recent decades, the management of renewable resources and the efficiency of food production systems have been among the most important research lines. Sustainable agriculture involves the successful management of agricultural natural resources to meet human needs while preserving natural resources and improving the quality of the environment. This approach must be biologically feasible, ecologically sustainable, economically permanent, and socially acceptable (Nayak and Patangray 2015). Sustainability could be achieved by minimizing the use of foreign inputs, maximizing the exploitation of natural processes, and optimal use of local resources (Nayak and Patangray 2015).

According to the results of this study, since the major part of non-renewable energy in the production of green onions and onions corresponds to fertilizers and electricity; using renewable energy to extract water from wells, managing water utilization, and using a more efficient irrigation system, as well as feeding plants with renewable sources can enhance the ratio of renewable energy sources in onion and green onion production. Therefore, in the new model, the use of wind turbines to generate electricity, microbial fertilizers (as an alternative to manure and chemical fertilizers) were investigated.

Microbial fertilizers are one of the approaches to enhance sustainability in agricultural production. Microbial fertilizers are harmless that can be produced from animal or plant waste. This fertilizer can increase soil water capacity with no environmental impacts on soil, air, and water. Exergy consumption and GHG emissions of microbial fertilizers are negligible (Özilgen 2017).

Wind electricity requires a lower amount of fossil energy (0.0404 MJ) and emits lower amounts of GHG (4.13 g $CO_2$eq.) per kWh of electricity generated (Costa et al. 2016). Exergy of wind-electricity was reported 2.29 MJ/kWh$_e$ (Yanga et al.).

The result of using renewable energy in the green onion and onion production system is shown in **Figure 4.** To examine the sustainability and dependence on renewable resources, CEnC, CExC, $CCO_2E$, CDP, RI, IP and SI were calculated in the new numerical model. The high value of CDP in onion production in the new strategy can be interpreted as a complete thermodynamic state. Thermodynamically, energy loss does not occur only in reversible processes. Accordingly, the use of renewable energy sources significantly declined energy consumption, exergy and GHG emissions of onions compared to green onions. The values of CDP, RI, IP, and SI for onion are more than green onion, which shows that in the new pattern, onion production will be more sustainable than onion. The reason for the higher sustainability of onions production (compared to onions) could be the higher human labor requirement of green onions.

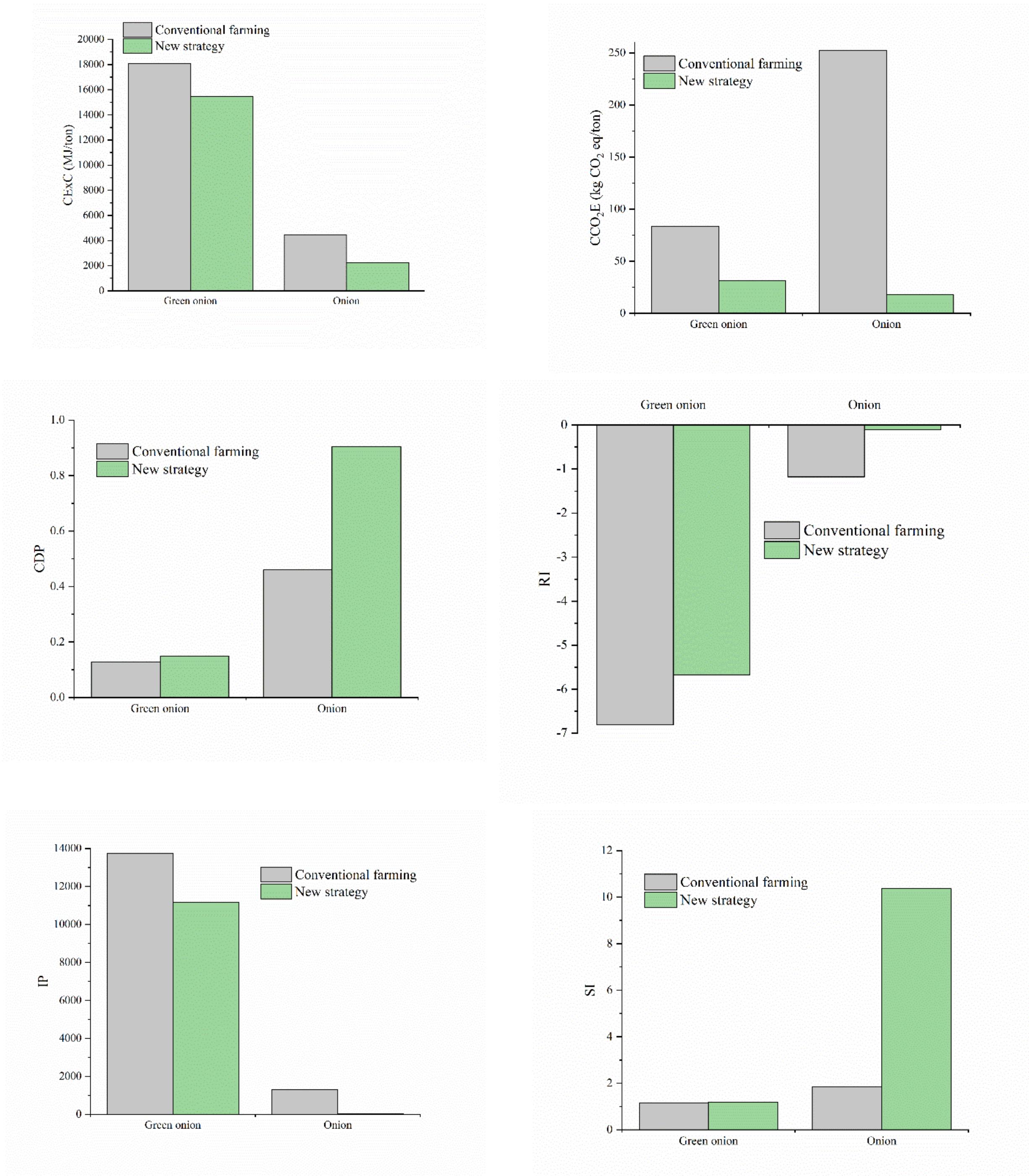



**Figure 4** The effect of using the new strategy on exergy, GHG emissions, CDP, RI, SI and IP of production of onions and green onions

## 4. Conclusion

Allium vegetables are the most consumed vegetables in the world. To study the sustainability of their agricultural system, a thermodynamic analysis was performed to assess the sustainability of the cultivation process of two similar plants namely onion (with the high human labor requirement) and green onion through an exergy-based approach. Exergy analysis identified the losses related to the production method. Measures to increase exergy efficiency can reduce environmental effects by reducing energy losses. The following results were obtained from this study:

(1) The energy consumption of onion production is 2.5 times that of green onion production which could be due to the high water requirement of onion. The irrigation operations (electricity and irrigation water) account for 80.67% of the total energy consumption of onions.

(2) The calculation of the sustainability index and exergy improvement potential showed that onion production caused lower environmental impacts and the green onion production process has a high potential to improve exergy efficiency.

(3) Manure played an important role in the exergy of the production process of onions; its replacement with microbial fertilizer can significantly improve the exergy efficiency and the sustainability of the production process.

(4) The impact of the new agricultural strategy on the green onions was less than onions, which made the production of green onions even more unsustainable than the production of onions, despite the use of renewable energy.

The results of this study showed how human labor requirement can influence energy consumption, GHG emissions, sustainability, and environmental indicators of two similar crops. The results of this study can help the decision-maker to develop onion varieties with low water requirements and to develop and to use farming machinery from planting to harvesting operations of products such as green onions.

**Appendix**

Small-scale agriculture is an operation that is highly dependent on human labor. As **Table A.1** shows the lack of consideration of human labor, shows that the exergy losses of green onion production are less than onions, and the analysis of sustainability indicators also shows that green onion agriculture is more sustainable than onions. In addition to the lack of consideration of human labor in onion thermodynamic analysis underestimates the energy consumption and exergy waste and overestimates sustainability indicators of onion production. While the results of the present study confirm the opposite of the above result and human labor should not be ignored in agricultural activities.

The chemical compositions of onion and green onion are listed in **Tables A.2 and A.3**, respectively. Calculation of availability flow was performed according to Özilgen and Sorgüven ( 2019). The availability flows of green onion and onion were obtained to be 2.32 and 2.04 $MJkg^{-1}$, respectively.

**Table A.1** Assessment of the onion and green onion cultivation process with an exergy-based approach without considering human labor

| Thermodynamic index | Green onion | Onion |
|---|---|---|
| CEnC (MJ/ton) | 670.33 | 2987.12 |
| CExC (MJ/ton) | 2678.20 | 3073.33 |
| CDP | 0.86 | 0.66 |
| RI | -0.16 | -0.51 |
| SI | 7.38 | 2.98 |
| IP (MJ/ton) | 49.16 | 347.18 |
| Exergy waste (MJ/ton) | 362.86 | 1032.96 |

**Table A.2** Composition of onion was obtained from Petropoulos et al (2019)

| Chemical composition | | Specific CExC | References |
|---|---|---|---|
| Carbohydrates | 11.92% | 16.5 | (Szargut, 2005) |
| Protein | 1.31% | 2.28 | (Dewulf et al., 2005) |
| Fat | 0.11% | 1.04 | (Dewulf et al., 2005) |
| Water | 86.12% | 0.05 | (Szargut et al., 1987) |
| Ash | 0.55% | 0.0305 | (Dewulf et al., 2005) |

**Table A.3** Composition of green onions was obtained from Abdelbagi Nasir Ahmed (1998)

| Chemical composition | | Specific CExC | References |
|---|---|---|---|
| Carbohydrates | 13.10% | 16.5 | (Szargut, 2005) |
| Protein | 1.00% | 2.28 | (Dewulf et al., 2005) |
| Fat | 050% | 1.04 | (Dewulf et al., 2005) |
| Water | 84.30% | 0.05 | (Szargut et al., 1987) |
| Ash | 0.50% | 0.0305 | (Dewulf et al., 2005) |

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