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ARTICLE

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Exergoenvironmental damages assessment in a desert-based agricultural system: A case study of date production

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Abstract

Developing countries, especially those in hot and dry areas, need more attention to achieve sustainable development as they apply excessive inputs in production processes. The present study aims to quantify the amount of environmental emissions and determine the most appropriate pattern of energy use in the date (*Phoenix dactylifera* L.) production process using thermodynamic analysis. The information was gathered through questionnaires and face-to-face interviews. From the results, cumulative exergy and energy demand for one Mg of date fruit production were calculated as 697 and 1640 MJ, respectively. Carbon dioxide emission was also measured at 197 kg Mg^{-1}. Moreover, cumulative exergy consumption illustrated that manure and diesel fuel consumption is high, though diesel fuel and N consumption are given the most cumulative energy demand. Renewability indicator, cumulative degree of perfection, and the recoverable exergy ratio value of the date fruit production process were calculated as 0.62, 2.68, and 4.32, respectively. The date's chemical exergy value was calculated to be 14.96 MJ kg^{-1}. Dates have a high chemical exergy value because of their high carbohydrate content and low water content. As a result, crop chemical combinations have a direct impact on the production process. The total direct greenhouse gas emissions induced by the inputs consumption were 310.02 kg Mg^{-1}. Emissions to air, soil, and water were 308.76, 5.60×10^{-1} and 6.96×10^{-1} kg Mg^{-1}. In general, date production in Khuzestan province is partially renewable.

Abbreviations: CCO_2E, cumulative carbon monoxide emissions; CDP, cumulative degree of perfection; CEnC, cumulative energy consumption; CExC, cumulative exergy consumption; CExD, cumulative exergy demand; CNEx, cumulative net exergy consumption; RER, recoverable exergy ratio; RI, renewability indicator.

1 | INTRODUCTION

Improper use of nonrenewable energy sources could result in a serious health issues, droughts, food shortages, and the extermination of numerous plant and animal species (Gorjian et al., 2020; Gorjian et al., 2019). Typically, fertile areas produce the vast majority of the world's agricultural output. Nevertheless, because those areas' capability to increase food production is limited, peripheral parts, including drylands and desert places, can play an effective role in increasing production. Drylands now encompass over 41% of the Earth's geographical surface and are home to one-third of the global population (Burrell et al., 2020). Developing agriculture in less suitable areas may be theoretically feasible in certain situations, but it would surely lead to poorer yields, the need for extra inputs, higher infrastructure expenses, all of which would boost production expenses, and energy consumption (FAO, 2019; Jahanbakhshi & Kheiralipour, 2019). It may also place a further strain on environmental structures and put the system's long-term viability in jeopardy. It also threatens human health and causes musculoskeletal disorders in developing countries, where most activities are performed by manpower (Hassani, Hesampour, et al., 2021). Therefore, it is essential to study the sustainability and long-term viability of various production systems in arid regions.

Conservation biology and sustainable production have long been important goals that require collaborative efforts and supportive policies. Generally, additional inputs of chemical fertilizer and manure can result in increased concentration of Hg, Zn, Cd, Cu, Pb, Ni, and Cr into the soil; movement of nitrate (NO_3) and phosphate with leaching and runoff water, respectively; and releasing ammonia (NH_3), nitrogen oxides (NO_x), and dinitrogen monoxide (N_2O) into the atmosphere (Eggleston et al., 2006).

Date (*Phoenix dactylifera* L.) is a monocotyledonous tropical plant in the genus of palms. Date fruit is edible and hangs in large clusters from branches, with large leaves and a hard core. The fruit has thin skin and a sweet taste. Depending on the species, the palm can reach a height of up to 20 m. Date trees have been grown as one of the main crops throughout the world, from south-central Asia to the northern part of Africa, California and Arizona in the United States, and parts of European countries (Johnson et al., 2015; Ortiz-Uribe et al., 2019). In 2017, the words produced about 7.5 million tons (Mohd Jaih et al., 2019). Egypt, Saudi Arabia, Iran, Algeria, and Iraq are responsible for 54% of the global date production (FAO, 2018). The date is the third most important plantation orchard crop in Iran, planted in 13 provinces. Khuzestan is the second-largest producer of dates in Iran. A total of 42 ha of land in Khuzestan is covered by date groves and >180,000 Mg of date are produced annually. The southern cities of Khuzestan (Abadan, Shadegan, Ahvaz, and Khorramshahr) have suitable conditions for growing this type of fruit because of their tropical weather (Ministry of Energy – Iran, 2020). The date fruit is shown as a rich source of sugar, protein, dietary fiber, minerals, and some vitamins (Siddiq et al., 2013). The date also is used as a medical treatment for cancer and other different chronic illnesses (Assirey, 2015). In general, date cultivation is very important in the world, but like other desert products, it has received little attention from researchers.

Core Ideas

- The renewability indicator and recoverable exergy ratio values of date production were calculated as 0.6 and 4.3.
- Crop chemical combinations have a direct impact on the date production process.
- The total direct greenhouse gas emissions induced by the inputs consumption was 310.02 kg Mg^{-1}.
- Emissions to air, soil and water were 308.76, 5.60 $\times 10^{-1}$ and 6.96 $\times 10^{-1}$ kg Mg^{-1}, respectively.

Many studies have examined the sustainability of various manufacturing systems from an energy and environmental emissions perspective, including grape (*Vitis vinifera* L.) (Elhami et al., 2019), onion (*Allium cepa* L.) (Elhami et al., 2021), apple (*Malus domestica* auct. non Borkh.) juice (Khanali et al., 2020), greenhouse strawberry (*Fragaria* sp.) (Hosseini-Fashami et al., 2019), and barley (*Hordeum vulgare* L.) (Payandeh et al., 2021), durum wheat (*Triticum durum* Desf.) (Failla et al., 2020), and oil bearing crops (Restuccia et al., 2013). In a study by Bamber et al. (2020), the effect of using wood or bark as mulch to reduce nitrogen dioxide (NO_2) emissions and increase soil organic matter in apple orchards was investigated. The results of the research indicated that mulch application in orchards is not a greenhouse gas mitigation approach. Furthermore, the production and spreading of mulch result in increased net life cycle greenhouse gas emissions. Jiang et al. (2021) studied environmental emissions of the wheat (*Triticum aestivum* L.) production process using chemical fertilizer, manure compost, and biochar-amended manure compost. Biochar-amended manure compost procedures reduced N_2O emissions. Clune et al. (2017) reviewed the production process of several agricultural goods in their research, but only one study was focused on the production process of dates.

A life cycle assessment approach and parametric and nonparametric procedures were used to assess dates planted in the Khuzestan Province of Iran by Hesampour et al. (2018) and Hesampour et al. (2021). Environmental pollution was primarily caused by pesticides, diesel fuel, and N fertilizer.

Another study showed that diesel fuel, chemical fertilizer, and irrigation water were the most important inputs for date production in Iran's Bushehr province, whereas manure and labor force were the least important inputs (Davani et al., 2011). However, quantification of greenhouse gas emissions and evaluation of energy consumption in the production of various products has a crucial contribution to identifying hotspots in supply chain management and as a consequence of reducing environmental risks (Deng et al., 2020). Not considering the quality of consumed inputs is a major problem and limitation, which received less attention from researchers in previous investigations (Sartor & Dewallef, 2017; Stanek et al., 2017). As a result, evaluating the performance of an energy conversion system with the help of energy analysis is not an effective and accurate method. Exergy analysis could be used as a creative solution to overcome this limitation. Exergy is a key approach for assessing the quality of natural resources during product production (Rasoolizadeh et al., 2021). Exergy analysis could assist farmers to make better quality energy use in crop production, resulting in lowered energy consumption and increasing the sustainability of production systems (Genç et al., 2017). In other words, increasing exergy productivity reduces the environmental effects of the entire manufacturing process (Sciubba & Wall, 2007). The concept of exergy is defined by the application of the first and second laws of thermodynamics. Thermodynamic techniques are commonly used in biosystems to evaluate the state of total processes. In this method, all inputs, as well as the chemical properties of the crop, are required to be considered in the computation (Bilgen & Sarıkaya, 2015). Cumulative exergy consumption (CExC) is a procedure of assessment in accordance with the concept of exergy. The entire exergy consumed by all inputs in the ultimate product-generating process is known as CExC (Nikkhah et al., 2021). In the thermodynamic strategy, with CExC, the cumulative degree of perfection (CDP) for crop-generation processes could be measured. The CExC method also could be computed to assess the crop production process's renewability indicator. Different forms of energy are contained in variable quantities and quality. Exergy knowledge helps to define these changes and monitor the optimization of energy balance. Analytical application of exergy also helps to find out the amount of energy wastage in processes that reach equilibrium. Ultimately, achieving sustainable development in agricultural production is dependent on paying attention to both the quality and the quantity of inputs consumed. The importance of this issue led many researchers to study exergy in the agricultural sector. Strawberry (Yildizhan, 2018), apples (*Malus pumila* Mill.) (Yildizhan et al., 2021), rice (*Oryza sativa* L.) (Nikkhah et al., 2021), maize (*Zea mays* L.) (Juárez-Hernández et al., 2019), drying nectarine [*Prunus persica* (L.) Batsch var. *nucipersica* (Suckow) C.K. Schneid.] slices in a hot air dryer (Jahanbakhshi et al., 2020), and quince (*Cydonia oblonga* Mill.) under a hot air dryer (Abbaspour-Gilandeh et al., 2020). In another study, Hesampour et al. (2022) assessed the amount of energy consumption, economic indicators, and cumulative exergy demand in greenhouse cucumber (*Cucumis sativus* L.) production by taking into account the greenhouse's structure. The results showed that substituting natural gas for diesel fuel in greenhouses could reduce the nonrenewable fossil index by 20.26%. In a research of pistachio nut (*Pistacia vera* L.), nectarine, peach [*Prunus persica* (L.) Batsch], and apple, Ordikhani et al. (2021) discovered that the nonrenewable and renewable fossil index had the highest value during the production stages of these items.

Because of the paucity of previous studies on exergy in date production, additional research is needed. The objectives of the present study are presented as follows:

- Determining the cumulative energy index in date crop production.
- Determination of cumulative exergy indices in order to determine nonrenewable fossil fuels, nonrenewable metals, nonrenewable minerals, and renewable water using Simapro software (Version 9.2.0.2.) (a perfect solution for those who want to drive sustainable change).
- Assessing the total amount of direct emissions (emissions from the consumption of inputs) within the entire production process.
- Quantifying the amount of carbon dioxide emitted in the production process.

2 | METHODOLOGY

2.1 | Overview of the research area, farming system, and data gathering

Khuzestan province is placed in the southwest (lat: 29˚58′; long: 32˚58′) of Iran. This region has hot desert climate according to the Köppen climate classification, and has faced a water crisis in recent years. This province is considered a "warm super-arid climate" according to national divisions. The cities surveyed have temperatures above 50 ˚C in June, July, and August, and temperatures above 45 ˚C in May and September. The maximum rainfall occurs in January, which is 45 mm, followed by February with 30 mm. The humidity in the summer months reaches 90%. Figure 1 exhibits the comprehensive layout of the studied location. This province plays a significant role in the production of dates. The date cultivation is predominantly spread in the southern cities of Khuzestan province. The study area included the cities of Abadan, Shadegan, Ahvaz, and Khorramshahr. A total of 100 questionnaires were used to collect the necessary information, along with interviews with farmers and Jahad agriculture firm specialists. In particular, the questionnaire was not distributed

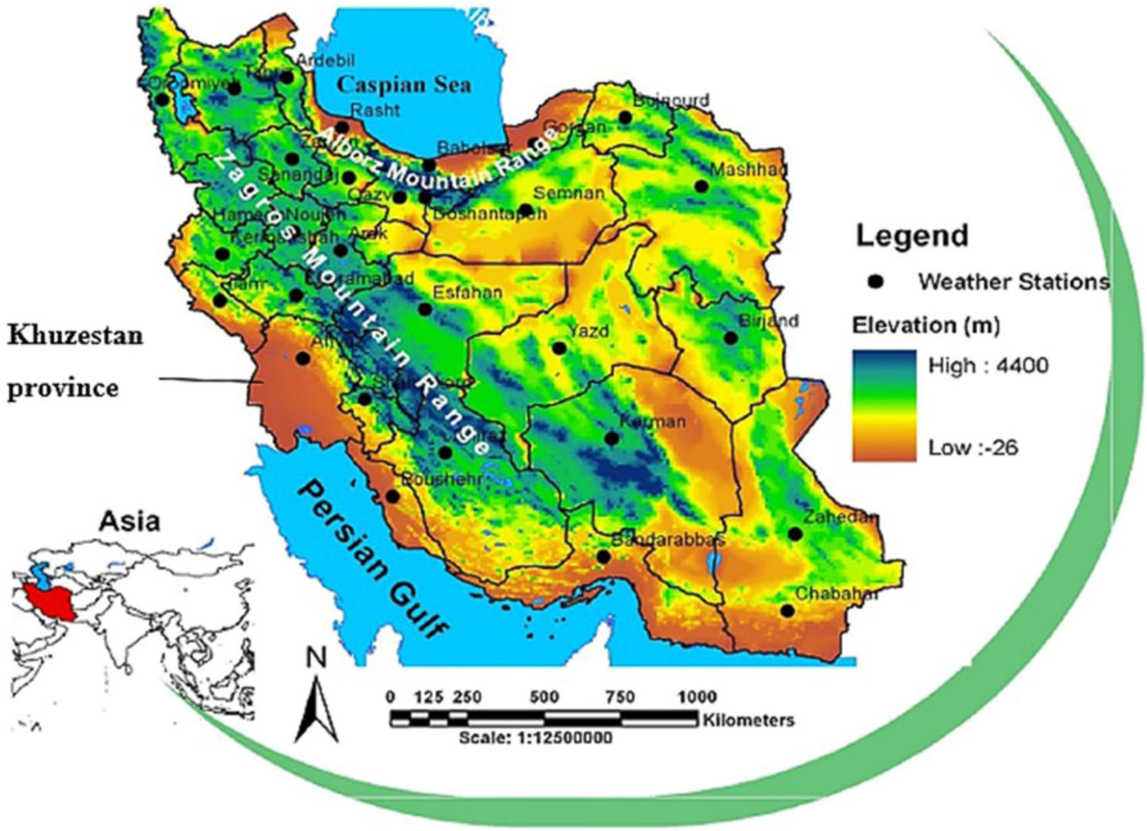

FIGURE 1 The actual location of Khuzestan province and its cities on a map of Iran

to farmers. Instead, face-to-face interviews were carried out with them, and information needed to analyze the data was collected. All data were taken and recorded by the authors themselves to increase accuracy. The required information was collected from 100 gardeners. Gardeners who were reluctant to cooperate were not considered. It should be noted that information about the amount of input consumption in the production process is also recorded in the state-owned Jihad Agricultural Company of Khuzestan Province. Additionally, agricultural jihad experts were engaged to ensure the data collection was as accurate as possible.

Separating the seedlings from the main tree is the first step in planting a date, which is done by manpower using a sharp-edged iron wedge. In preparation for planting seedlings, the land is plowed, and planting rows are marked on the ground with a ruler. Next, holes are dug to a depth of 1–1.5 m^2. In some cases, farmers fill half of the hole with animal manure. Depending on whether or not a plant or another tree is planted between the date trees, the distance between the date trees varies between 8 and 10 m^2. In the cities of Khorramshahr and Abadan, irrigation is done by furrow irrigation using the water from the sea. Diesel pumps are commonly used for extracting water from wells in areas distant from the sea. Chemical fertilizers for date trees were not commonly used until a few years ago. However, they are now being used by some farmers, particularly those who cultivate crops like alfalfa (*Medicago sativa* L.) between the date trees. Nitrogen fertilizer is generally applied in the spring, whereas animal manures are applied once every 2 yr, in the autumn after harvest. One of the most important operations in the production process of dates is pollination, which has a substantial influence on product quality. Pollination time can vary from March to May, depending on the temperature and type of date. In the study area, palm growers keep date clusters in sacks to prevent them from insect and bird damage. The product is harvested and marketed by human resources after it is ripe.

2.2 | An overview of the necessity and method of conducting research

It is indispensable to determine and optimize models of input consumption in the agricultural sector. However, customary energy measurement approaches in accordance with the first law of thermodynamics are inefficient in calculating the quality of energy consumed and energy losses (Nikkhah et al., 2021; Szargut, 2005). Accordingly, the exergy procedure was used to tackle the problem, which is according to the second law of thermodynamics. This method makes it possible to analyze all qualitative aspects of the production process and

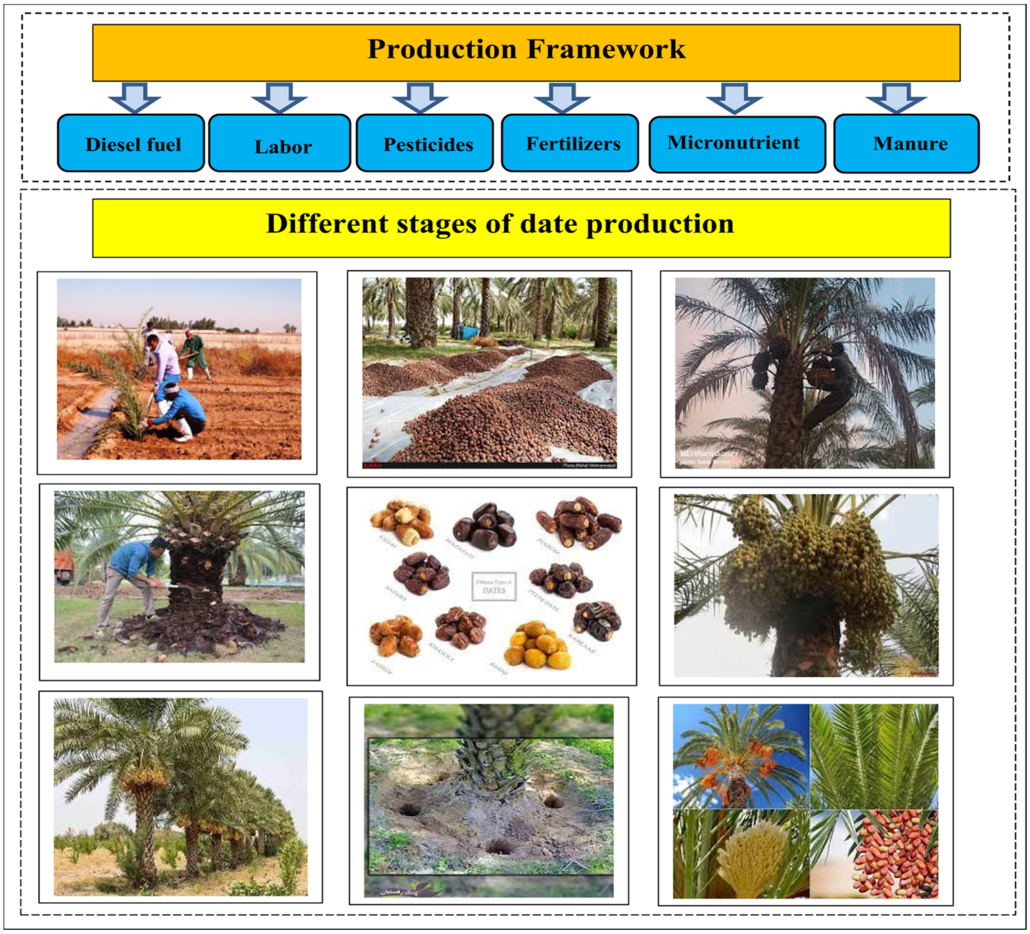

FIGURE 2 Different stages in the production of dates and considered inputs in the manufacturing process

energy losses (Chowdhury et al., 2020). In particular, through using exergy-based sustainability parameters, it is possible to optimize energy efficiency and manage the stability of the production system (Chowdhury et al., 2020; Hepbasli, 2008). In this case, cumulative exergy consumption in the date production process was analyzed. Ultimately, the recommendations have been given to minimize the exergy losses and increase the efficiency of date fruit production. In this regard, the functional unit (production of 1 t of date product) and the system boundary were identified in the initial stage of this research (Figure 2). Next, all consumed inputs in the production process were calculated based on the functional unit. Also, direct emissions from input consumption into the air, soil, and water were measured based on Table 1. The emissions result from diesel fuel consumption were also calculated by using the ecoinvent database and Microsoft Excel 2019 (Tables 2 and 3). The ecoinvent database contains greenhouse gas releases of various layers into the air, soil, and groundwater owing to input production in the European region. This information is extremely relevant for environmental impact investigations on crop production in Iran (Fathollahi et al., 2018; Marzban et al., 2021).

2.3 | Exergy flow assessment

In this research, cumulative energy consumption (CEnC), CExC, cumulative carbon dioxide emissions (CCO_2E) indicators are examined. For this purpose, CDP, renewability indicator (RI), and the recoverable exergy ratio (RER) indices were defined, and the following formulas were applied to calculate them (Balkan et al., 2005; Ozilgen et al., 2019). Cumulative exergy consumption was computed by taking into consideration work processes and heat in accordance with Equations (1–4) (Yildizhan, 2018).

Mass balance:

$$\sum m_{\text{in}} = \sum m_{\text{out}} \quad (1)$$

Energy balance:

$$\sum (mh)_{\text{in}} - \sum (mh)_{\text{out}} = W - Q \quad (2)$$

Exergy balance:

$$\sum (mb)_{\text{in}} - \sum (mb)_{\text{out}} + \sum \left(1 - \frac{T_0}{T_k}\right) Q_k - W = I \quad (3)$$

TABLE 1 The diffusion coefficients and conversion coefficients in the calculation of various inputs in palm production

Emissions	Coefficient	Transformation of emissions	References
Emissions of fertilizers			
$\frac{kgN_2O-N}{kgNinfertilizerused}$	0.01 (to air)	Transformation from kg $N_2O - N$ to kg $N_2O = \left(\frac{44}{28}\right)$	Eggleston et al. (2006)
$\frac{kgNH_3-N}{kgNinfertilizerused}$	0.1 (to air)	Transformation from kg $NH_3 - N$ to kg $NH_3 = \left(\frac{44}{28}\right)$	Eggleston et al. (2006)
$\frac{kgN_2O-N}{kgNinatmosphericdeposition}$	0.01 (to air)	Transformation from kg $N_2O - N$ to kg $N_2O = \left(\frac{44}{28}\right)$	Elhami et al. (2021)
$\frac{kgNO_x-N}{kgN_2Oinfertilizerandmanure}$	0.21 (to air)		Eggleston et al. (2006)
$\frac{kgPemission}{kgPinfertilizerandmanure}$	0.05 (to water)	Transformation from kg P_2O_5 to kg $P = \left(\frac{62}{142}\right)$	Elhami et al. (2021)
$\frac{kgNO_3^--N}{kgNinfertilizerandmanure}$	0.03 (to water)	Transformation from kg $NO_3 - N$ to kg $NO_3 = \left(\frac{62}{14}\right)$	Elhami et al. (2021)
Emissions of manure			
$\frac{kgNH_3-N}{kgNinmanureused}$	0.2 (to air)	Transformation from kg manure to kg $NH_3 = \left(\frac{17}{14}\right)$	Eggleston et al. (2006)
$\frac{kgN_2O-N}{kgNinmanureused}$	0.01 (to air)	Transformation from kg manure to kg $N_2O = \left(\frac{44}{28}\right)$	Eggleston et al. (2006)
Emissions from manpower			
$\frac{kgCO_2}{man-hmanpower}$	0.7 (to air)		Eggleston et al. (2006)

TABLE 2 On-farm emissions for palm production (functional unit 1 Mg)

Direct emissions to air	Diesel fuel
	kg MJ^{-1}
Carbon dioxide (CO_2)	74.5
Sulfur dioxide (SO_2)	2.41×10^{-2}
Methane (CH_4)	3.08×10^{-3}
Benzene	1.74×10^{-4}
Cd	2.39×10^{-7}
Cr	1.19×10^{-6}
Cu	4.06×10^{-5}
Dinitrogen monoxide (N_2O)	2.86×10^{-3}
Ni	1.67×10^{-6}
Zn	2.39×10^{-5}
Benzo (a) pyrene	7.16×10^{-7}
Ammonia (NH_3)	4.77×10^{-4}
Se	2.39×10^{-7}
Nitrogen oxides (NO_x)	1.06
Carbon monoxide (CO)	0.15
Particulates (2.5 µm)	0.107

Entropy balance:

$$\sum S_{\text{generation}} = \sum (mb)_{\text{out}} - \sum (mb)_{in} - \sum \frac{Q_k}{T_k} \quad (4)$$

Equations (1) and (2) advert to the law of mass and energy conservation of all inputs used in the process of date production. In Equations (3) and (4), Q_k and W denote the amount of heat and work, respectively. m, h, T_0, and T_k stand for mass, hentalpy, and temperature, respectively. I and S also exhibit the system's irreversibility and enthalpy of the system (Nikkhah et al., 2021; Özilgen & Sorgüven, 2016; Ozilgen et al., 2019; Yildizhan & Taki, 2018). The term b indicates the flow availability as reported in Equation (5):

$$b = b^{\text{th}} + b^{\text{ch}} \quad (5)$$

where b^{ch} represents chemical exergy, and b^{th} signifies physical exergy.

To compute the cumulative exergy of consumption of each input, the exergy constants of the inputs were acquired from the preceding research. These coefficients were measured in accordance with the law of mass and energy conservation. Table 4 denotes the equivalent exergy and energy consumption of inputs. Different types of fertilizers applied in date production have various numerical quantities for specific CExC and CEnC, so to calculate the amount of these indicators, fertilizers were divided into three categories: N, phosphate, and K. The same classification should be performed for chemical pesticides, but considering that herbicides are the only chemical pesticides used in the study area, specific CExC and CEnC were estimated for the herbicide

TABLE 3 Heavy metal diffusion coefficients into the soil

	Heavy metals						
Formula	**Cd**	**Cu**	**Zn**	**Ni**	**Cr**	**Hg**	**Pb**
$\frac{\text{mgheavymetal}}{\text{kgNinfertilizer}}$	6	26	203	20.9	77.9	0.1	5,409.00
$\frac{\text{mgheavymetal}}{\text{kgphosphateinfertilizer}}$	90.5	207	1923.00	202	1245.00	0.7	154
$\frac{\text{mgheavymetal}}{\text{kgKinfertilizer}}$	0.2	8.7	11.3	4.5	10.5	0.1	1.5
$\frac{\text{mgheavymetal}}{\text{kgmicroinfertilizer}}$	0	160	102	0	0	0	0
$\frac{\text{mgheavymetal}}{\text{kgmaterialofcowmanure}}$	1.52	99	469	19.05	8.7	0.085	16.2

TABLE 4 Equivalent data for calculating cumulative exergy consumption (CExC) and cumulative energy consumption (CEnC) in date production

Inputs	Specific CExC	Specific CEnC	References
	MJkg^{-1}		
Diesel fuel	53.2	57.5	Yildizhan & Taki (2018)
Herbicide	32.7	198.8	Yildizhan and Taki (2018), Yildizhan et al. (2021)
Fertilizers			
N	32.7	78.2	Taki & Yildizhan (2018), Esmaeilpour-Troujeni et al. (2021)
Phosphate (P_2O5)	7.52	17.5	Taki and Yildizhan (2018), Nikkhah et al. (2021)
Potassium oxide (K_2O)	4.56	13.8	Yildizhan et al. (2021), Özilgen & Sorgüven (2011)
Manure	5.33	0.35	Pimentel (1991), Fadare et al. (2010)
Water	0.00425	1.02E-03	Yildizhan & Taki (2018)

consumption during the production process. The numerical quantity of specific CO_2, as one of the most critical greenhouse gases emitted into the air, soil, and water from each input consumption, was also calculated in Appendix A. The chemical exergy value of the date was determined as 14.96 MJ kg^{-1}.

2.3.1 | CDP and RI assessment

At this stage, the CDP, which is the proportion of the exergy of the crop to the total natural input exergies and nonrenewable resources, was also computed (Amiri et al., 2020). Likewise, the greater the numerical value of the CDP index, the lower the exergy losses. In this study, CDP was measured based on Equation (6) (Yildizhan & Taki, 2018).

$$\text{CDP} = \frac{(mb)_{\text{product}}}{\sum(m\text{CExC})_{\text{rawmaterials}} + \sum(m\text{CExC})_{\text{fuels}}} \quad (6)$$

Cumulative exergy loss or cumulative net exergy consumption (CNEx) is measured based on Equation (7) (Berthiaume & Bouchard, 1999):

$$\text{CNEx} = \text{CExC} - \text{Ex}_{\text{p}} \quad (7)$$

Where CExC is the total exergy of all consumed resources during the stages of the product, Ex_{p} is determined as the exergy of the crop production. The restoration work W_{r} is calculated in Equation (8) by adding the cumulative net exergy consumption of production and the cumulative net exergy consumption of waste treatment (Berthiaume et al., 2001).

$$W_{\text{r}} \cong \text{CNEx}_{\text{p}} + \text{CNEx}_{\text{waste}} \quad (8)$$

In the above equation, cumulative net exergy consumption of waste treatment was assumed to be zero because of a lack of accessibility to proper information about polluted water. The RI, which determines the renewability or nonrenewability of the entire process, was computed based on the difference between output and input exergy divided by the output of produced work as stated in Equation (9) (Berthiaume et al., 2001).

$$\text{RI} = \left(W_{\text{p}} - W_{\text{r}}\right) / W_{\text{p}} \quad (9)$$

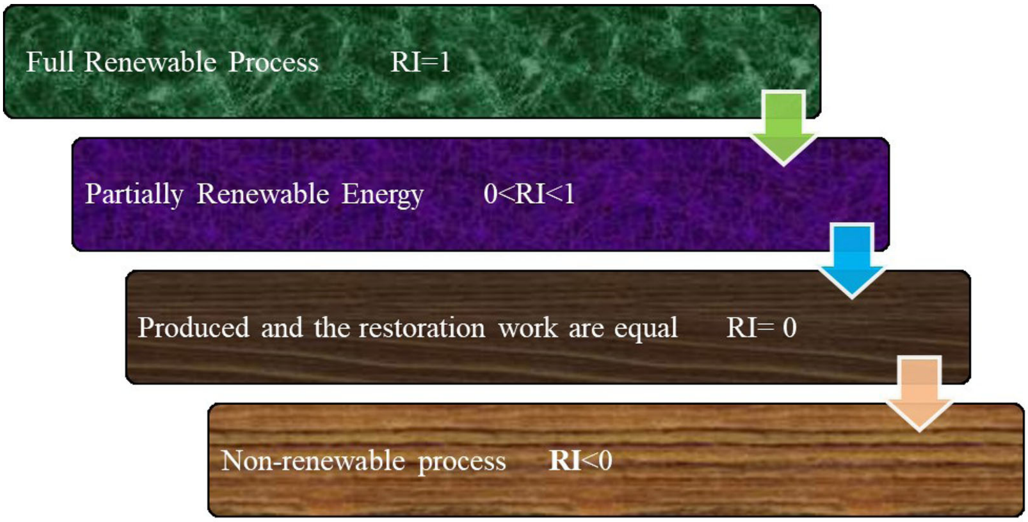

FIGURE 3 Renewability indicator (RI) definition (Berthiaume et al., 2001)

Because the ultimate product in this study is allocated to the date fruit crop, W_p is equal to the exergy of the output (crop). Therefore, the RI equation was altered to Equation (10):

$$RI = (Ex_p - W_r)/Ex_p \quad (10)$$

Based on the value of this index, the degree of renewability of the date production process in Khuzestan province, Iran, was determined. Figure 3 demonstrates the definitions of diverse quantities.

2.3.2 | Recoverable exergy ratio

In this study, a new thermodynamic definition within the scope of crop production processes was made. It is assumed that the date kernel will be replanted in the soil (it was common practice in the past to plant dates in this manner). In other words, part of the date crop is replanted on the ground after consumption. In this study, it was assumed that the kernels and seedlings that were separated from the main tree would be reused. This is called the "RER". There was insufficient information about date seedlings in the literature. The chemical exergy value of the date fruit kernel was determined as 24.11 $MJkg^{-1}$. The RER value of the date fruit production process was calculated with Equation (11).

$$RER = \frac{Recoverableexergy}{Totalexergyinput} \quad (11)$$

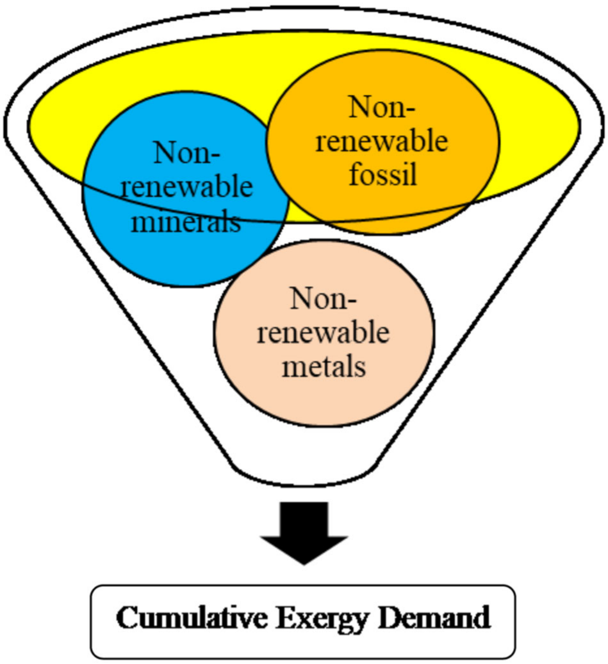

FIGURE 4 The cumulative exergy demand (CExD) indices in date production systems

2.4 | Cumulative exergy demand using SimaPro software

In this study, the indicators presented in Figure 4 were also calculated using SimaPro software (Version 9.2.0.2) and the equivalent database 2.0. This sustainability software is excellent for industrial designers, decision-makers, and sustainability professionals because it is dependent on robust science and life cycle thinking. Life cycle assessment allows for knowledgeable choices, encourages sensible decisions, and minimizes the ecological footprint of goods and operations. The exergy cumulative demand index refers to the amount of exergy removed from nature to furnish a commodity, in which the exergy takes into account all the resources used in the production process. In general, the concept of exergy is presented for fossil, nuclear, hydropower, biomass, other renewables, water, minerals, and metals categories. There are 112 different resource characterization factors included in the computation (Bösch et al., 2007; PRé & various authors, 2019).

$$\mathrm{CExD} = \sum_i m_i \times \mathrm{Ex}_{(\mathrm{ch}),i} + \sum_j n_j \times r_{\mathrm{ex}-e(\mathrm{k,p,n,r,t}),j} \quad (12)$$

where CExD = cumulative exergy demand (MJ-eq), m_i = mass of inputs i (kg), $\mathrm{Ex}_{(\mathrm{ch}),i}$ = exergy of each input i (MJ-eq kg^{-1}), n_j = quantity of energy j (MJ), $r_{\mathrm{ex}-e(\mathrm{k,p,n,r,t}),j}$ = exergy/energy ratio of inputs j (MJ-eq MJ^{-1}), ch = chemical, k = kinetic, p = potential, n = nuclear, r = radiative, and t = thermal exergy.

3 | RESULTS AND DISCUSSION

3.1 | An overview of the studied indicators and input consumption per Mg of dates

In this study, CExC, CEnC indicators, $\mathrm{CCO_2E}$, CDP, and RI for date production were estimated using thermodynamic analysis, and nonrenewable fossil, nonrenewable minerals, nonrenewable metals, renewable water, and renewable potential indices were also used through Simapro Software (Version 9.2.0.2). The information used to grow date fruit and the necessary inputs spent throughout the production process was obtained from questionnaires completed by 100 date producers and interviews with agricultural Jahad experts in the study area. In the first step, the CEnC index, which is the total energy consumption in the production process, such as the energy required for material extraction and disposal of raw and auxiliary materials, was calculated (Yildizhan et al., 2021). To achieve this goal, the functional unit was determined to be 1 Mg. Generally, date production in the study area is not characterized by the frequent use of chemical fertilizers and pesticides. The alfalfa crop is widely used to reduce N fertilizer usage. Traditional methods are also used to control pests. Date seedlings are submerged in running water for 10 d, and all pests are eradicated. Figure 5 depicts the type and quantity of inputs consumed in the production of 1 ton of date crop. Based on Figure 5, N is used more than other chemical fertilizers in the date production process. Furthermore, livestock manure supplies a significant portion of the date tree's nutrient requirements. Farmyard manure can improve soil structure and increase organic matter. However, excessive use of manure has some negative impacts on plants and trees.

3.2 | CEnC flow assessment

The results of the CEnC calculation are shown in Figure 6. The CEnC used in the production process was estimated to be 1,640.26 MJ Mg^{-1}. The largest participant in the total energy input was found as diesel fuel (46.37%). In this region, diesel pumps are used to extract and irrigate date gardens. As for other crops, diesel fuel accounted for the majority of total energy consumption in apple production (70% of total energy consumption) (Khanali et al., 2020), and walnut (*Juglans nigra* L.) (40.18%) (Khanali et al., 2021). The inefficiency of the irrigation system framework, outdated diesel pumps, and the lack of sufficient knowledge among farmers about modern irrigation systems, as well as the required volume of irrigation, are the reasons for increasing energy consumption. In general, in places where diesel pumps are used to extract water, more attention needs to be allocated to their maintenance. The use of renewable energy, especially solar energy for water extraction, can reduce the use of diesel fuel, which leads to a reduction in the CEnC index. Nitrogen, with a CEnC of 359.72 MJ Mg^{-1}, was recognized as the second most energy-intensive input, which accounted for 21.93% of the total input energy consumption. The simultaneous growing of alfalfa among the rows of date trees, planting chemical fertilizers for easier root access to fertilizers, cultivating cover crops, and crop rotation are some of the techniques to reduce chemical fertilizer use. Precision agriculture is another technique aimed to limit chemical fertilizer consumption, which determines the precise amount of fertilizer needed at different stages of growth. Furthermore, soil testing can be another viable option to achieve this goal. On the other hand, by using common optimization methods such as data envelopment analysis or genetic algorithms, diesel fuel consumption can be optimized. In fact, these methodologies estimate the efficiency of production units (each date orchard is considered as a unit) and determine the reduction potential of each input, allowing the management sector to focus more on the inputs that have the largest potential for reduction. In the study of Hesampour et al. (2021), technical efficiency, sensitivity analysis, and economic evaluations in date production were investigated. According to data envelopment analysis, it is possible to reduce total energy consumption by 10.15%. Manure is the third energy-intensive input, accounting for 18.05% of the CEnC index. Nevertheless, the CEnC index is less affected by other chemical fertilizers (phosphate and potassium) and chemical toxins. In other words, the use of phosphate and potassium fertilizers as well as micronutrients in date cultivation in the Khuzestan province is very limited. In a study on apples, Yildizhan et al. (2021)

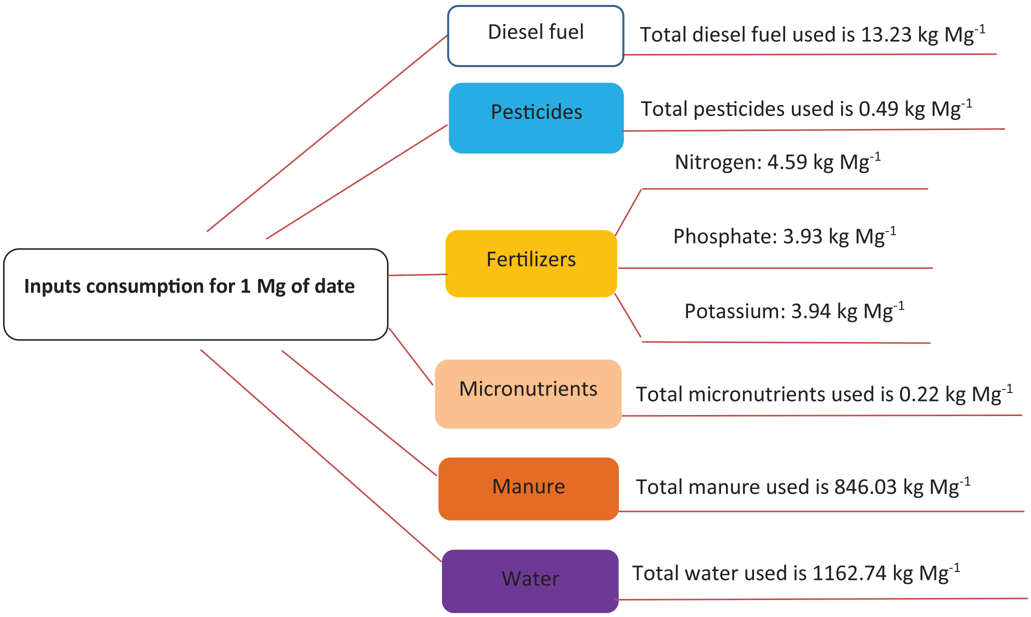

FIGURE 5 Inputs used for 1 Mg of date production

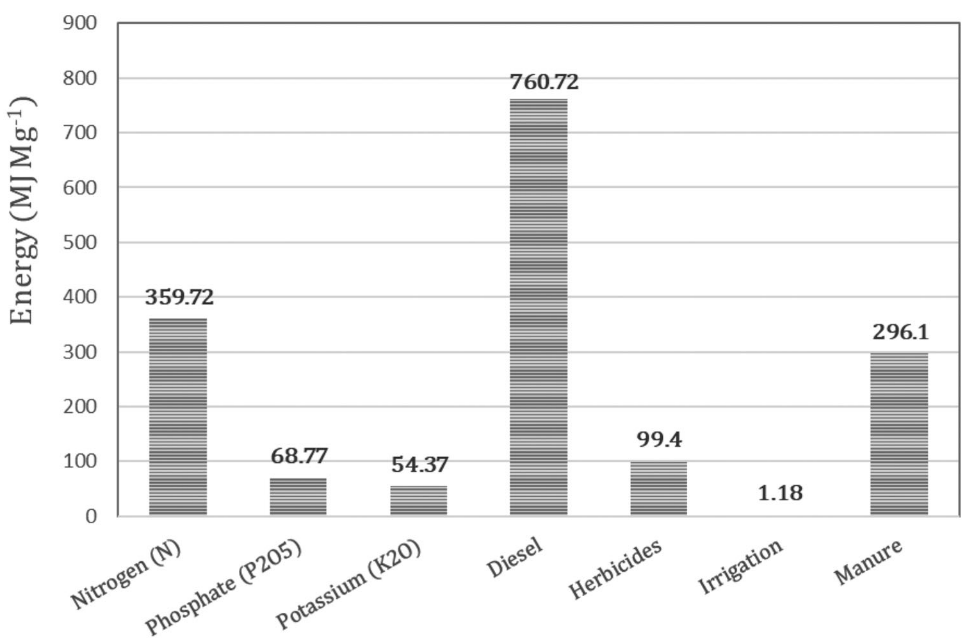

FIGURE 6 Cumulative energy consumption for palm date production

discovered that animal manure and diesel fuel have the greatest cumulative energy, followed by pesticides and electricity consumption. However, in a study on apples in the Semirom district of Isfahan, Iran, Naderi et al. (2020) found that diesel fuel and chemical toxins had the highest energy consumption with 56 and 12%, respectively. Nonrenewable fossil resources accounted for the largest amount of CEnC, which is associated with fossil fuel expenditure in irrigation pumps. These findings are consistent with earlier research (Naderi et al., 2020; Taki & Yildizhan, 2018). However, N's CEnC is the highest in other researches (Ghasemi-Mobtaker et al., 2020; Pishgar-Komleh et al., 2020; Yildizhan, 2018).

3.3 | CExC flow assessment

The CExC assessment for crop production denotes assessing the probabilities of overall production systems and attempting

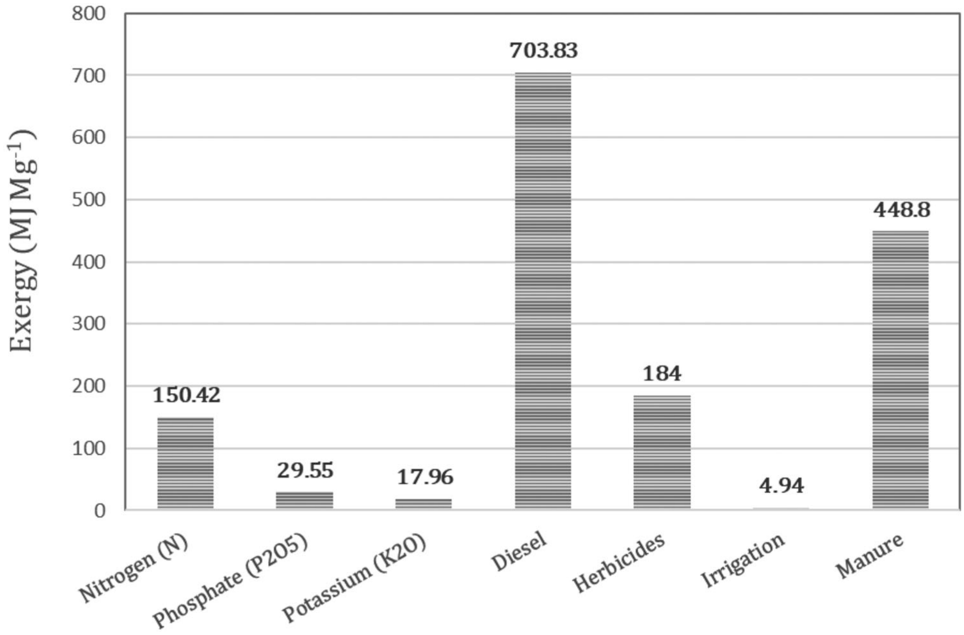

FIGURE 7 Cumulative exergy consumption for palm date production

to increase efficiency. Reduced CExC can help preserve natural resources for future generations, as well as decrease greenhouse gas emissions and promote human living conditions. The CExC for 1 Mg of date fruit output in the study area is shown in Figure 7. The total CExC is estimated to be around 5,576 MJ Mg^{-1}. Based on Figure 7, animal manure and diesel fuel inputs with 4,483.8 and 703.8 MJ Mg^{-1}, respectively, have the largest contribution to the CExC index. Herbicides and N fertilizers are the third and fourth most important inputs in the CExC index, with about 184 and 150 MJ Mg^{-1}, respectively. Figures 7 and 8 illustrate that the cumulative energy and exergy of fertilizer inputs like phosphate (P_2O_5) and potassium (K_2O) are low, indicating that these fertilizers were used appropriately during the production process. According to the results, it can be inferred that diesel fuel and animal manure have an important role in date production optimization. As a result, management should focus on the consumption of these two inputs in order to boost production sustainability. The outcomes of the assessment indicate that animal manure and diesel fuel have the potential to be applied more effectively than in the current situation. These energy resources could promote the quality of the date production process, but when the use of them is improper, environmental emissions into the air, soil, and water can pose a risk to human health, as well as reduce economic benefits. By implementing the consumption pattern presented in this study, the manufacturing sector can contribute to implement the United Nations Sustainable Development Goal (Goal 12), which emphasizes the pattern of sustainable consumption and production. The present study is the first to examine CEnC and CExC indicators in the date production process, so the indicators calculated in the present study were compared with those measured in other fruits and vegetables. In the study of Yildizhan et al. (2021), animal manure and electricity consumption input had the highest participation in the CExC index in the apple production process, which is in line with the findings of the current investigation. Yildizan (2018) reported that the rate of animal manure participation in the CExC index in the strawberry production process is 5,430 MJ Mg^{-1}, which accounts for ~62% of the total CExC. Sorgüven and Ozilgen (2012) estimated the CExC factor for yogurt manufacturing and determined it to be 74,655 MJ for 960 kg unwrapped nonfat yogurt. In the study by Nikkhah et al. (2021) on different rice varieties, diesel fuel consumption had the highest participation in the CExC index for all varieties except in the Mare.

3.4 | CDP and RI in date production

In this study, the CDP index was used to estimate the exergy efficiency of the production process. The CDP is calculated as the proportion of the output exergy of the date fruit to the CExC of all inputs such as N, phosphate, potassium, diesel, manure, irrigation, and herbicides (Bardant et al., 2018). The CDP index is influenced by both the chemical features of the date and the CExC index. As a result, this component is influenced by the input and output exergy of date generation (crop chemical structure). In other words, the higher the amount of exergy of the crop (dates) and the lower the cumulative exergy of the production process, the higher the value of the CDP index. As CDP is high, it indicates that the manufacturing process is low in exergy losses, and the

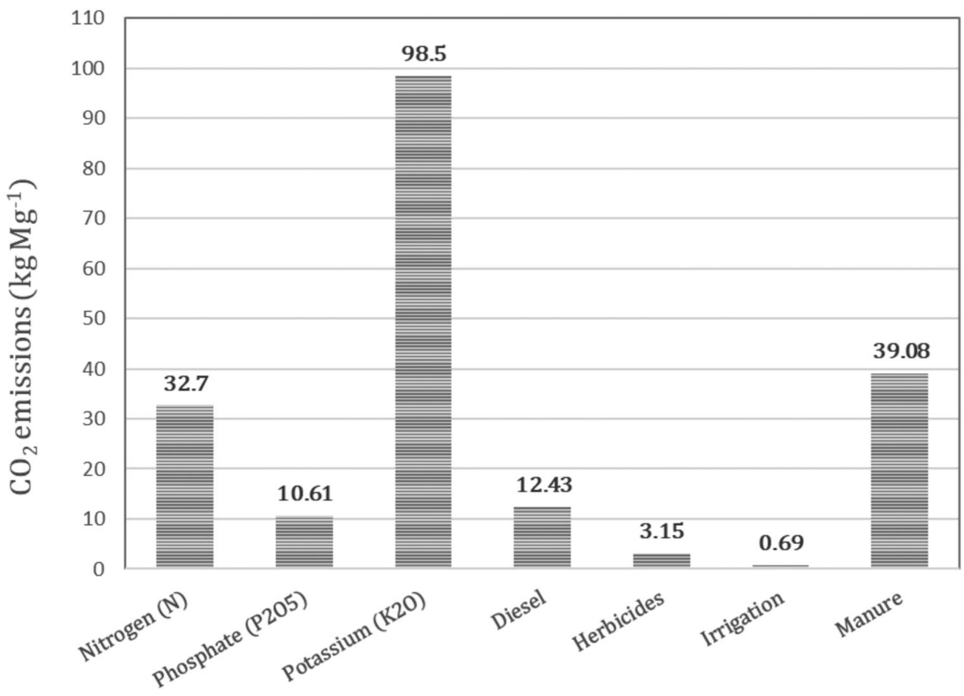

FIGURE 8 Cumulative carbon dioxide emissions (CCO_2) value for date palm production

renewability of the production process is high. Then, if the CDP indicator has a high value, it means that the manufacturing process is well-managed and ecologically sustainable. On the other hand, the lower CDP score reveals improper management. Increasing the use of renewable energy in the date production process is one approach to raise the CDP index. In this study, the value of the CDP index for 1 Mg of date production was calculated according to the amount of input consumption mentioned in the system boundary and exergy numerical quantity of dates. Based on the results, the chemical exergy value of dates was computed as 14.96 MJ kg^{-1}. The CDP value of the date production process was calculated as 2.68. The exergy losses index was measured at 9,384 MJ. In different researches, the amount of CDP index was calculated. The CDP index in cucumber production is 0.23 (Taki & Yildizhan, 2018), 0.92 and 0.98, respectively, for soybeans and olives (*Olea europaea* L.) (Özilgen & Sorgüven, 2011), and 7.96 for 'Luna' rice cultivar (Nikkhah et al., 2021). Amiri et al. (2020) reported the quantity of CDP for the commercial and traditional canola (*Brassica napus* L.) systems as 1.8 and 0.28, respectively. Yildizhan and Taki (2018) calculated the amount of this index in the greenhouse tomato (*Solanum lycopersicum* L.) production system as 1.25. As well, the values of CDP in the open field generation system (in southern Marmara and Tokat) have been 0.84 and 1.62, respectively. The CDP index in this study is higher than that in the production of cucumber, soybean, olive, canola, and tomato products, which could be attributable to the date crop's high exergy compared with other crops. Based on the study by Nikkhah et al. (2021), the CDP index for different varieties of rice differed. This was attributed to differences in the output exergy of each variety. In an examination of various canola production processes, Esmaeilpour-Troujeni et al. (2021) uncovered that semi-mechanized systems with greater sustainability indicators pose lower CExC scores.

In this study, the RI indicator was estimated to specify the rate of renewability of the date production process. The outcomes indicated that the RI index had a numerical value of 0.62 based on the inputs used. Therefore, it could be inferred that the date production process in the study area is partially renewable. To boost the RI index score, it is recommended to reduce the quantity of nonrenewable resources like diesel fuel in the production process. Esmaeilpour-Troujeni et al. (2021) calculated the RI index for the canola manufacturing process. Based on the results, the RI was 0.73, indicating that the canola production process is partially renewable. In the study of Pelvan and Ozilgen (2017) on black tea [*Camellia sinensis* (L.) Kuntze], the value of this index was computed as −1.35, which signifies that tea production is nonrenewable in their study area. In general, a high numerical quantity of the CDP index implies that the exergy losses of the production process are low, and the renewability index is high. This denotes that the production system is in line with the 1st, 12th, and 13th United Nations goals of ensuring sustainable consumption and production patterns.

TABLE 5 Direct emissions to air, soil, and water in one Mg of date production

Direct emissions	Diesel fuel	Fertilizers and manure	Human labor	Chemical pesticides	Total quantity of emissions
					kg
Emissions to air					
Carbon dioxide (CO_2)	55.50	3.36	26.67		85.53
Sulfur dioxide (SO_2)	1.79×10^{-2}				0.0179
Methane (CH_4)	2.29×10^{-3}				2.29×10^{-3}
Cd	1.78×10^{-7}				1.78×10^{-7}
Cr	8.86×10^{-7}				8.86×10^{-7}
Cu	3.02×10^{-5}				3.02×10^{-5}
Dinitrogen monoxide (N_2O)	2.13×10^{-3}	15.96			15.96
Ni	1.24×10^{-6}				1.24×10^{-6}
Benzo (a) pyrene	5.33×10^{-7}				5.33×10^{-7}
Ammonia (NH_3)	3.55×10^{-4}	206.0218			206.0223
Se	1.78×10^{-7}				1.78×10^{-7}
PAH (polycyclic hydrocarbons)	5.84×10^{-5}				5.84×10^{-5}
Nitrogen oxides (NO_x)	7.89×10^{-2}	0.963			1.04
Carbon monoxide (CO)	1.11×10^{-1}				1.11×10^{-1}
Particulates (2.5 µm)	7.97×10^{-2}				7.97×10^{-2}
Emissions to soil					
Cd		1.67×10^{-3}			1.67×10^{-3}
Cu		8.48×10^{-2}			8.48×10^{-2}
Pb		3.91×10^{-2}			3.91×10^{-2}
Ni		1.70×10^{-2}			1.70×10^{-2}
Cr		1.27×10^{-2}			1.27×10^{-2}
Hg		7.55×10^{-5}			7.55×10^{-5}
Zn		4.05×10^{-1}			4.05×10^{-1}
Diazinon				6.02×10^{-5}	6.02×10^{-5}
Emissions to water					
Nitrate (NO_3)		0.610			0.610
Phosphate		0.086			0.086
Total direct emissions	55.79	227.56	26.67	6.02×10^{-5}	310.02

3.5 | Calculation of CO_2 emissions and direct releases

The date generation process was reviewed in this part based on environmental parameters, and CCO_2 emission was determined (Figure 8). The total CO_2 emitted into the environment because of input consumption was calculated based on the cumulative method of 197.16 kg Mg^{-1}. The highest CO_2 emissions (49.95%) come from potassium fertilizer, which is commonly used in the early stages of garden creation. Manure and N, with 19.82 and 16.58 kg Mg^{-1}, respectively, are the other contributors to the total CO_2 emitted into the environment. The CCO_2 emissions can be lowered by improving manure-spreading efficiency and using precision farming techniques. Generally, some farmers reduce or eliminate the use of chemical fertilizers by cultivating alfalfa in between the rows of palm trees at the same time. Therefore, to reduce the emissions caused by chemical fertilizers, farmers should be encouraged to cultivate cover crops at the same time. Applying fertilizer around the seedlings is another way to increase the efficiency of fertilizer application, which facilitates plant accessibility to the required nutrients. In the research by Yildizhan (2018) on apple production, animal manures, electricity, and water consumption played the main roles in the CO_2 emissions. In the study by Yildizan and Taki (2018), diesel fuel consumption in the greenhouse heating system was the main contributor to the total CO_2 emissions in the tomato production process in Turkey. Pelvan and Ozilgen (2017) indicated that diesel fuel, natural gas, and electricity were the three main factors contributing to CO_2 emissions into the air, soil, and water in the production process of black tea.

The products that are produced are consumed. But in this study, it is assumed that some parts of the crops are replanted in the ground. The kernels and seedlings of the crops are reused. It is described by the RER. There was not enough information in the literature about the kernels of palm trees; that is why it is considered that the date kernel is planted in the ground again. The chemical exergy value of the date fruit kernel was determined as 24.11 MJ kg^{-1}. The RER value of the date fruit production process was calculated to be 4.32. In this study, direct emissions (emissions from input consumption) were also calculated in terms of functional units (Tables 1, 2, and 3).

From the results, it was determined that the total direct emissions induced by the inputs consumption were 310.02 kg Mg^{-1}. Emissions to air, soil and water are 223.22, 5.60×10^{-1} and 6.96×10^{-1} kg Mg^{-1}, respectively. As shown in Table 5, the ammonia (NH_3) and carbon dioxide (CO_2) emissions made up 66.45 and 27.58%, respectively, of total emissions into the air. The ratio of Zn, Cu, and Pb emissions to total emissions to the soil from chemical fertilizers and farm manure was measured to be 72.30, 15.12 and 6.98%, respectively. Chemical and animal fertilizers accounted for 227.56 kg Mg^{-1} of total emissions into the air, soil, and water. The participation rates of these inputs (chemical and animal fertilizers) in emissions to air was 73.29, and approximately all the emissions in water and soil are from chemical and animal fertilizers consumption. Based on Table 5, the contribution of diesel fuel to emissions into the air is 55.50 kg Mg^{-1}, which is 18.06% of total emissions into the air. Elhami et al. (2021) analyzed the economic indicators and environmental pollution of various onion production systems. The results of this research revealed that 42.64 and 33.97% of the total emissions into the air, soil, and water in seed and transplanting systems were attributed to ammonia, respectively. Furthermore, animal manure applied during the production process was reported to be the major source of ammonia emissions. These outcomes are consistent with the findings of the present study and clearly demonstrate the effect of animal manure on ammonia emissions.

3.6 | CExD assessment using Simapro

The total CExD index in the production of 1 Mg of dates was calculated to be 825.03 MJ. The share of the nonrenewable fossil index was estimated to be 771.39 MJ, which is equivalent to 93.49% of the total CExD indicated. This index was largely influenced by diesel fuel and N fertilizer, with 742.06 and 328.59 MJ, respectively. The nonrenewable metals index was calculated to be 24.32 MJ, which is 2.98% of the total CExD index. Nitrate and phosphate fertilizers contributed the most to this index, with 21.36 and 7.32 MJ, respectively. Based on Figure 9, phosphate and N fertilizers are also the largest contributors to the nonrenewable minerals index. This study represents the first attempt to examine the CExD index on date production. However, CExD index has been evaluated in a few studies. In the research of Ghasemi Mobtakar et al. (2020) on wheat, biocides and N fertilizer were the most effective inputs in the nonrenewable minerals index. Ordikhani et al. (2021) calculated phosphate fertilizer as the most contributing factor in the nonrenewable minerals index for apple, peach, and nectar production, which agrees with the results of the present study.

4 | CONCLUSIONS

The present study aimed to conduct an exergoenvironmental damages assessment in a desert-based agricultural system using thermodynamic analysis and CExD on date production. Based on the results, the CEnC index for 1 Mg of date fruit production was 1,640.26 MJ. While the total CExC index was 696.99 MJ. The CDP index was calculated to be 2.68, which signifies high exergy efficiency. The RI value was determined to be 0.62. Therefore, the palm production process is a partial renewable process. On the other hand, the cause for the high CDP and RI values of the palm generation process is the high chemical exergy value of the date fruit, which was established as 14.96 $MJkg^{-1}$. The reason for the high chemical exergy value of dates is the high rate of carbohydrate and low water content of dates in chemical combination. As a result, the chemical features of date directly influence manufacturing processes. Diesel fuel has the biggest influence on diminishing exergy efficiency and reducing the renewability of the production process of all the inputs used in the date supply chain. The total amount of direct emissions in the production process was 310.02 MJ Mg^{-1}, in which fertilizers, manure, and diesel fuel played the most influential role in emissions to air, and chemical fertilizers had the most participation in soil pollution. It can be ameliorated by installing upgraded or maintained electromotors, elevating gardener consciousness of the accurate crop water requirements, preventing flooding irrigation and using sprinkler irrigation systems, creating a favorable and uniform slope in gardens to ease water movement, implementing crop rotation to retain soil moisture, and, most notably, applying a photovoltaic thermal system. According to the results of the study, N fertilizer reduction can have a significant impact on nonrenewable metals, and potassium fertilizer reduction can have a significant impact on mineral indicators. This can be lessened using variable rate technologies, soil testing and amendment according to soil and species conditions, the use of nanotechnology to develop environmentally friendly chemicals, and the usage of biofertilizers. It is suggested that future research investigate the

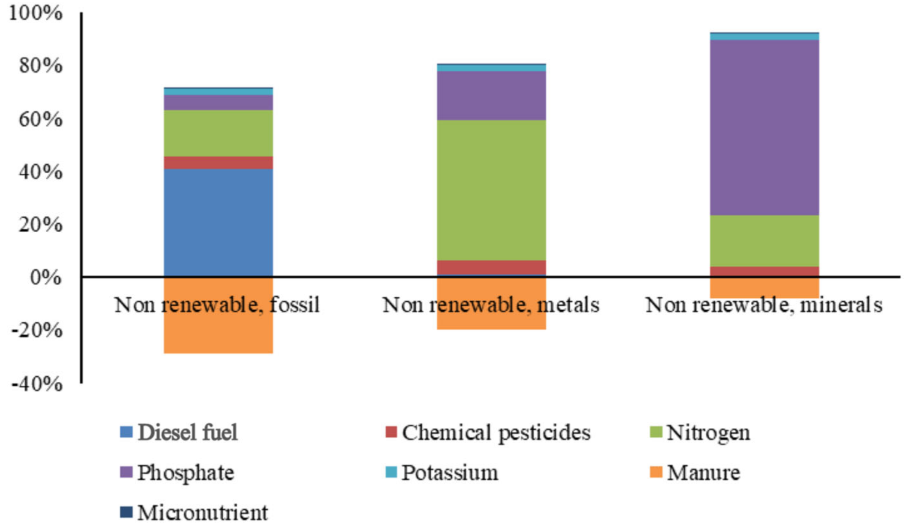

FIGURE 9 Cumulative exergy demand (CExD) index in the production of one Mg of date

impact of using wood and bark on increasing soil organic matter and reducing the need for chemical fertilizers in date orchards. It is also suggested that the potential of using solar energy and replacing it with diesel fuel be examined from an economic, energy, and environmental perspective.

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AUTHOR CONTRIBUTIONS

Reza Hesampour: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft; Writing – review & editing. Mehrdad Hassani: Conceptualization; Data curation; Writing – review & editing. Hasan Yıldızhan: Conceptualization; Methodology; Software; Visualization. Sabina Failla: Validation; Writing – review & editing. Shiva Gorjian: Writing – review & editing.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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Appendix A: Coefficients for computation of CO_2 emissions in date production

Inputs	Specific CO_2	References
	$MJkg^{-1}$	
Diesel fuel	0.94	Yildizhan & Taki (2018)
Herbicide	6.3	Ozilgen & Sorgüven (2016)
Fertilizers		
N	0.09	Yildizhan & Taki (2018)
Phosphate (P_2O5)	0.15	Yildizhan and Taki (2018)
Potassium (K_2O)	0.51	Yildizhan and Taki (2018)
Manure	0.0462	Ozilgen & Sorgüven (2016)
Water	5.95E-04	Ozilgen and Sorgüven (2016)