



# Energy Sustainability in Viticulture in a Hot Climate Region in Brazil

Cássio Vinícius de Souza<sup>1</sup> · José Aires Ventura<sup>1</sup> · Jacimar Luis de Souza<sup>1</sup> · Diolina Moura Silva<sup>2</sup> · Carlos Alberto Sangali de Mattos<sup>1</sup>

Received: 29 August 2023 / Accepted: 12 February 2024 / Published online: 7 March 2024

© Der/die Autor(en), exklusiv lizenziert an Springer-Verlag GmbH Deutschland, ein Teil von Springer Nature 2024

## Abstract

On a global scale, agricultural systems consume approximately one third of the energy available on the planet. Viticulture is an important agricultural activity for Brazil, mainly due to the characteristics of family production and because it is a product with high added value. Studies addressing the energy balance in grape production in Brazil have rarely been conducted. The objective of this study was to evaluate the energy balance in family-based viticulture in a hot climate region in Brazil. The mean production data of 11 table grape orchards (*Vitis labrusca* L.), located in the municipality of Guarapari, state of Espírito Santo/Brazil, were used. The energy coefficient (MJ) of each component involved in the production process per hectare (ha) of cultivation was quantified. The energy inputs were categorized as direct and indirect energy. The study considered ripe grapes and vine pruning residues as available energy. The direct input energy accounted for 60.62% (18,515.5 MJ), and the indirect input accounted for 39.38% (12,027.01 MJ). Renewable energy contributed 24% (7180.27 MJ) and nonrenewable energy contributed 76% (23,362.24 MJ) of the entries. The ripe grapes and pruning residues corresponded to 78% (192,771.88 MJ) and 22% (52,820.00 MJ), respectively, of the outputs. The total energy efficiency (TEE), grape energy efficiency (GEE) and grape energy conversion (GEC) were 8.04, 6.31, and 0.53 kg MJ<sup>-1</sup>, respectively. The grape specific energy (GSE) and net available energy (NAE) were 1.87 MJ kg<sup>-1</sup> and 215,049.37 MJ, respectively. The sustainability levels were considerably increased when the pruning residues were converted into viticulture inputs.

**Keywords** Energy · Family farming · Pruning residues · Sustainability · Tropical viticulture

## Introduction

Viticulture is an important agricultural industry for Brazil and for the state of Espírito Santo, primarily because of its family production characteristics and because it is a product with high added value. Among the strategic guidelines outlined for the grape production chain, productivity, quality and sustainability are priorities. The path defined for the advancement of these guidelines is to increase the area of cultivation, number of producers and use of cultivars most appropriate to the soil and climate conditions of the state. In addition, the adoption of appropriate techniques for implantation, production and postharvest are prioritized (Pedeag 3, 2015). Climate change scenarios indicate that winegrowers will need to grow vines at higher atmospheric CO<sub>2</sub> levels and at warmer temperatures (Theron and Hunted 2022). This requires adaptation of cropping systems, as well as the intensification of more sustainable practices.

On a global scale, current agricultural systems consume approximately one-third of all available energy on the planet (Pestisha et al. 2023). Therefore, increasing

✉ Cássio Vinícius de Souza  
cassiovsouza@gmail.com

José Aires Ventura  
ventura@incaper.es.gov.br

Jacimar Luis de Souza  
jacimarsouza@yahoo.com.br

Diolina Moura Silva  
diolina.silva@ufes.br

Carlos Alberto Sangali de Mattos  
santateresa@incaper.es.gov.br

<sup>1</sup> Capixaba Institute for Research, Technical Assistance and Rural Extension—Incaper, Afonso Sarlo Street, 160, Bento Ferreira, 29052-010 Vitória, ES, Brazil

<sup>2</sup> Postgraduate Program in Plant Biology (Plant Physiology), Federal University of Espírito Santo/Brazil—UFES, Fernando Ferrari Avenue, 514, Goiabeiras, 29075-910 Vitória, ES, Brazil

the efficiency of energy use in the sector is a necessary step to reduce socioenvironmental problems and increase sustainability. GHG emissions in agricultural production arise from the use of machinery, consumption of diesel oil, use of chemical fertilizers and consumption of electricity; clearly, this increase in energy use leads to an increase in GHG emissions (Baran et al. 2022). Thus, the estimate of agricultural crop yield based on energy use generates very important information for farmers, the government, and industries (Khoshroo et al. 2018; Nouri-khjelagh et al. 2023) and for society in general. Energy indicators can contribute to the formatting of public policies for everyone involved in the agricultural production chain.

An evaluation of the impact of agricultural technologies is important for estimating their technological, economic, social and environmental effects and benefits (Moraes et al. 2018), especially as they relate to the development of more sustainable production systems. Sustainability, in most agroecosystems, is seen only in the economic, social and environmental dimensions. However, when the energy dimension is considered, wine agroecosystems have the ability to be considerably more sustainable (Mercenaro et al. 2014; Zambon et al. 2018).

Carbon sequestration performed by cultivated plants is the result of the conversion of solar energy into biomass (gross primary productivity). Much of this energy is fixed and used by cultivars in their metabolic processes, while some of it dissipates into the environment as heat. The remaining fixed energy is the net primary productivity, which is the amount of energy incorporated into the plant tissues; it is the difference between the processes of photosynthesis and respiration (Menezes Neto et al. 2018). It is extremely important to evaluate and understand energy chains within viticultural agroecosystems. When less energy is dissipated during agricultural production, the process is more efficient (Campos et al. 2019; Malwe et al. 2022).

Studies addressing the energy balance in table grape production are very scarce. Thus, there is a need to generate information on these aspects. Improvements in energy efficiency not only help increase competitiveness by reducing costs but also minimizes GHG emissions and environmental impacts. In addition, they enable crop performance to be identified, regardless of the size of the farm and the practices adopted (Karimi and Moghaddam 2018; Mohseni et al. 2019; Malwe et al. 2022). Based on this scenario, the objective of this study was to evaluate the energy balance in family-based viticulture in the warm climate region of the state of Espírito Santo, Brazil, thus enabling the sustainability impacts of the activity to be measured.

## Material and Methods

### Location, Characteristics and Delimitation of Production Systems

The study was conducted in the municipality of Guara-pari-ES, Brazil (latitude 20° 38' 25.10" and longitude 40° 28' 53.80"). The climate of the region according to the Köppen classification is Aw—tropical climate, with dry winters. The mean annual temperature is 23.30°C, the mean annual rainfall is 1307 mm, and the mean annual relative humidity is 80.00%.

The choice of region was based on the existence of a well-defined and structured program of rural development through viticulture; the effective participation of the Government of the State of Espírito Santo in the program through the Research and Technical Assistance and Rural Extension services (TARE); and the lack of information on the energy performance of viticulture. The results of this study can be extrapolated to other warm regions of the state of Espírito Santo and Brazil.

The evaluated crops were planted in 2018, with the cultivars 'Niagara Rosada' and 'Isabel Precoce' (*Vitis labrusca L.*), with a spacing of 3.00 meters between rows and 2.00 meters between plants, grown via a trellis system. The trellis cover was constructed of mesh woven with polyethylene threads (shade) to prevent bird attack. All cultivar treatments were performed as recommended for the cultivar.

### System Delimitation

The delimitation of the system was based on average production data from 11 orchards owned by family farmers. The energy costs were estimated per hectare (ha) of cultivation. The follow-up period consisted of three harvests (2020, 2021 and 2022) with an average duration of 120 days, from pruning to harvest. The data were obtained through technical visits and interviews with family farmers, as well as through the availability of data by the official services of Rural Extension of Institute of Research, Technical Assistance and Rural Extension-Incaper in the state of Espírito Santo.

All inputs were accounted for, including human labor, machinery and equipment, gasoline, electricity, chemical fertilizers, manure, insecticides, fungicides, irrigation water and others inherent to the production process. Solar energy, whether in the form of radiation or heat, was not taken into account in this study because, according to Keshavarz Afshar et al. (2013), this energy is considered a free subsidy in the energy analysis of agricultural systems. The energy cost related to crop formation activities was not taken into account. Rahmani et al. (2022) report the average lifespan

of a vine between 75 and 80 years, which, based on the energy costs of formation and the lifespan of the vine, makes the energy input negligible.

The energy inputs were categorized into direct energy (human labor, fuels and lubricants, pesticides, limestone, fertilizers and irrigation water) and indirect energy (energy used in the manufacture of equipment, construction and installations and other inputs necessary for production). For the latter, energy depreciation was used, taking into account the time of use and useful life of the equipment. Inputs were also classified as renewable (human labor, manure and irrigation water) and nonrenewable (fuel, chemicals and machinery) (Karimi and Moghaddam 2018; Elhami et al. 2019; Malwe et al. 2022; Soltani et al. 2023).

## Energy Components, Coefficients and Indicators

The energy inputs (direct and indirect energy) in the evaluated system and their respective energy coefficients are presented in Table 1.

In the evaluated properties, irrigation is performed via the drip system. In a drip irrigation system, water is applied in a controlled manner through drops that reach the soil directly from a polyethylene pipe. The creation of this process was based on the observations of Turco et al. (2018), who reported a demand of 0.4716 MJ for each m<sup>3</sup> of water used for drip irrigation systems. Considering the implementation and energy depreciation, Timsina et al. (2022) recommend a value of 0.1431 MJ for each m<sup>3</sup> of water consumed. The

**Table 1** Energy inputs and respective energy coefficients in one hectare for grape production in a family farming system in the hot climate region of the state of Espírito Santo/Brazil

| Energy Input                    | Unit           | Equivalent Energy (MJ Unit <sup>-1</sup> ) | Reference                                  |
|---------------------------------|----------------|--|--|
| <i>Direct Energy</i>            |                |  |  |
| Human labor                     | hour           | 1.96                                       | Timsina et al. (2022); Kaab et al. (2019)  |
| Dolomitic limestone             | ton            | 170.00                                     | Silva et al. (2020)                        |
| N                               | kg             | 54.80                                      | Paris et al. (2022)                        |
| P <sub>2</sub> O <sub>5</sub>   | kg             | 10.30                                      | Paris et al. (2022)                        |
| K <sub>2</sub> O                | kg             | 7.00                                       | Paris et al. (2022)                        |
| Poultry manure                  | ton            | 300.00                                     | Keshavarz Afshar et al. (2013)             |
| Gasoline                        | L              | 31.88                                      | Aseffe et al. (2019)                       |
| Lubricating oil                 | L              | 42.37                                      | Turco et al. (2018)                        |
| Insecticides                    | kg             | 199.00                                     | Keshavarz Afshar et al. (2013)             |
| Fungicides                      | kg             | 92.00                                      | Keshavarz Afshar et al. (2013)             |
| Irrigation water                | m <sup>3</sup> | 0.62                                       | Timsina et al. (2022); Turco et al. (2018) |
| <i>Indirect Energy</i>          |                |  |  |
| Backpack sprayer 20L            | kg             | 102.26                                     | Seflek et al. (2018)                       |
| Stapler                         | kg             | 48.96                                      | Seflek et al. (2018)                       |
| Pruning scissors                | kg             | 48.96                                      | Seflek et al. (2018)                       |
| Mechanized backpack brushcutter | kg             | 48.96                                      | Seflek et al. (2018)                       |
| <sup>a</sup> Other tools        | kg             | 48.96                                      | Seflek et al. (2018)                       |

<sup>a</sup>Refers to the sum of other hand tools used in the production process

**Table 2** Energy inputs and respective energy coefficients, referring to the construction of the trellis for one hectare of vine cultivation (cultivars 'Niagara Rosada' and 'Isabel Precoce')

| Energy Inputs                                  | Unit | Quantity  | Equivalent Energy (MJ Unit <sup>-1</sup> ) | Total energy value (MJ) |
|--|------|-----------|--|-------------------------|
| <sup>a</sup> Eucalyptus cuttings 2.60 × 0.15 m | kg   | 31,023.00 | 14.08                                      | 436,803.84              |
| <sup>b</sup> 2.1 mm galvanized wire            | kg   | 880.00    | 62.80                                      | 55,264.00               |
| <sup>b</sup> Stretcher of 5/8"                 | kg   | 36.00     | 62.80                                      | 2260.80                 |
| <sup>b</sup> Steel Rope 1/4"                   | kg   | 164.00    | 62.80                                      | 10,299.20               |
| <sup>c</sup> Polyethylene roofing (shading)    | kg   | 776.30    | 46.49                                      | 36,090.19               |
| <sup>b</sup> Band "U" of 1/2"                  | kg   | 60.00     | 62.80                                      | 3768.00                 |
| <sup>d</sup> Human labor                       | hour | 200.00    | 1.96                                       | 392.00                  |
| <i>Total trellis construction</i>              |      |           |  | 544,878.03              |

<sup>a</sup>Bersch et al. (2018)

<sup>b</sup>Steinmann et al. (2019)

<sup>c</sup>Palmay et al. (2021)

<sup>d</sup>Timsina et al. (2022)

energy equivalent of  $0.62 \text{ MJ m}^{-3}$  of water used for irrigation was adopted in this study. The energy composition of the supporting structure of the plants (treated trellis) (Table 2) was estimated from the energy coefficients of its constructive components established by several authors, as well as the direct energy used in its construction. Its average useful life (5475 days) was calculated based on the useful life of its construction components.

Useful energy was considered to be that available in the form of ripe grapes and crop pruning residues, which are disposed of in the soil. The energy coefficient adopted for the grapes was  $11.80 \text{ MJ kg}^{-1}$  of ripe fruit (Hamedani et al. 2011). According to Zambon et al. (2018), vine pruning residues have an energy equivalent of  $19.00 \text{ MJ kg}^{-1}$ .

The energy analysis was performed based on the energy indicators recommended in the related literature (Keshavarz Afshar et al. 2013; Moraes et al. 2018; Turco et al. 2018; Khoshroo et al. 2018; Rahmani et al. 2022; Ahmadbeyki et al. 2023), according to the Eqs. 1, 2, 3, 4 and 5:

$$\text{Total energy efficiency (TEE)} = \frac{\text{Power output (MJ)}}{\text{Energy inputs (MJ)}} \quad (1)$$

$$\text{Grape energy efficiency (GEE)} = \frac{\text{Power output of grapes (MJ)}}{\text{Energy inputs (MJ)}} \quad (2)$$

$$\text{Grape energy conversion (GEC)} = \frac{\text{Production of grapes (kg ha}^{-1}\text{)}}{\text{Energy inputs (MJ)}} \quad (3)$$

$$\text{Grape specific energy (GSE)} = \frac{\text{Energy inputs (MJ)}}{\text{Production of grapes (kg)}} \quad (4)$$

$$\text{Net available energy (NAE)} = \text{Energy outputs (MJ)} - \text{Energy inputs (MJ)} \quad (5)$$

## Results and Discussion

The direct and indirect energy inputs related to viticulture in the warm climate region of the state of Espírito Santo/Brazil for each hectare of cultivation were  $18,515.50 \text{ MJ}$  and  $12,027.01 \text{ MJ}$ , respectively. Table 3 presents all energy inputs, as well as their dimensional units, quantities, energy coefficients and total energy value.

Of all the energy that enters the conversion system ( $18,515.50 \text{ MJ}$ ),  $60.62\%$  refers to direct energy. In the composition of this input, nitrogen fertilizer was the most relevant at  $21.89\%$  ( $6685.60 \text{ MJ}$ ). It was followed by human labor, poultry manure and irrigation water, at  $9.1\%$  ( $2780.06 \text{ MJ}$ ),  $9.04\%$  ( $2760.00 \text{ MJ}$ ) and  $5.37\%$  ( $1640.21 \text{ MJ}$ ), respectively, of the total energy inputs,

dolomitic limestone,  $\text{P}_2\text{O}_5$  and  $\text{K}_2\text{O}$  had low percentages of participation, at  $1.56$ ,  $1.89$  and  $1.97\%$ , respectively (Fig. 1).

Karimi and Moghaddam (2018), when evaluating the energy input in grape orchards in Shahriar, Iran, pointed to the nitrogen input,  $35\%$  ( $11,241 \text{ MJ}$ ) in relation to the total inputs. Uzun and Baran (2022), when evaluating energy flows in Turkish viticulture, found that fertilizers composed  $49.66\%$  of total inputs, were the most significant component. Rahmani et al. (2022) evaluated energy flows in conventional and semi-mechanized systems in viticulture. The authors obtained, respectively,  $47.00\%$  ( $12,401.25 \text{ MJ}$ ) and  $44.00\%$  ( $11,045.38 \text{ MJ}$ ) nitrogen intake. Notably, there is a high dependence on chemical fertilizers in the conversion systems evaluated by the authors. In the present study, the participation of nitrogen fertilization was also significant but lower. This is because part of the nitrogen fertilization is supplied via organic and green manures. In addition, chemical nitrogen fertilization is recommended and adopted in lower doses, thus resulting in lower dependence on this synthetic input. The expressive energetic participation of the nitrogen input in the conversion systems is closely associated with the production of its sources. Fertilizers with reactive nitrogen are produced by the Haber-Bosch synthesis process. In this process, natural gas ( $\text{CH}_4$ ) is burned to produce hydrogen, which reacts with  $\text{N}_2$  under high temperature and high pressure to form ammonia ( $\text{NH}_3$ ) (Robertson and Vitousek 2009; Matassa et al. 2023).

When analyzing the energy balance of viticulture in the semiarid region of Iran, Khoshroo et al. (2018) reported an energy demand of  $2465.68 \text{ MJ ha}^{-1}$  for human labor. This value is lower than that found in the present study ( $2780.06 \text{ MJ ha}^{-1}$ ). In the production system evaluated by the authors, agricultural activities are intensely mechanized. Kamari et al. (2021), when evaluating energy consumption in grape production in the province of Ilam, Iran, found an energy demand of  $945.77 \text{ MJ ha}^{-1}$  for human labor input, resulting in a participation of  $3.33\%$  of the total energy entering the system. In the present study, due to the nature of family farms, most crop treatments are performed manually (pruning, spraying, fertilization, weeding, green pruning and harvesting). There is no use of herbicides. The only mechanized activity found was mowing, which was performed with a mechanized backpack mower. According to Silva et al. (2019), viticulture has a high demand for labor, especially on family farms. This justifies a greater energy expenditure for the human labor input in the present study, which accounted for  $9.10\%$  of the total inputs (Fig. 1).

The use of manual labor in practically all activities explains the low share of energy input from fossil fuels (gasoline and lubricating oil) used in the evaluated systems. These inputs corresponded to only  $3.14\%$  ( $960.43 \text{ MJ}$ ) of the total energy entering the system (Fig. 1 and Table 3). This denotes a lower dependence on fossil fuel, which is

**Table 3** Energy inputs per hectare of cultivation for the viticulture activity practiced in a hot climate region in the state of Espírito Santo/Brazil

| Energy Inputs                    | Unit           | Quantity | Useful life (days) | Equivalent Energy (MJ Unit <sup>-1</sup> ) | Total energy value (MJ) |
|----------------------------------|----------------|----------|--------------------|--|-------------------------|
| <b>Direct Energy</b>             |                |          |                    |  |                         |
| Human labor                      | hour           | 1418.40  | –                  | 1.96                                       | 2780.06                 |
| Dolomitic limestone              | ton            | 2.80     | –                  | 170.00                                     | 476.00                  |
| N                                | kg             | 122.00   | –                  | 54.80                                      | 6685.60                 |
| P <sub>2</sub> O <sub>5</sub>    | kg             | 56.00    | –                  | 10.30                                      | 576.80                  |
| K <sub>2</sub> O                 | kg             | 86.00    | –                  | 7.00                                       | 602.00                  |
| Poultry manure                   | ton            | 9.20     | –                  | 300.00                                     | 2760.00                 |
| Gasoline                         | L              | 28.00    | –                  | 31.88                                      | 892.64                  |
| Lubricating oil                  | L              | 1.60     | –                  | 42.37                                      | 67.79                   |
| Insecticides                     | kg             | 5.60     | –                  | 199.00                                     | 1114.40                 |
| Fungicides                       | kg             | 10.00    | –                  | 92.00                                      | 920.00                  |
| Irrigation water                 | m <sup>3</sup> | 2667.00  | –                  | 0.62                                       | 1640.21                 |
| <i>Total Direct Energy</i>       |                |          |                    |  | <i>18,515.50</i>        |
| <b>Indirect Energy</b>           |                |          |                    |  |                         |
| Backpack sprayer 20L             | kg             | 4.40     | 1825.00            | 102.60                                     | 29.59                   |
| Stapler                          | kg             | 0.80     | 1825.00            | 48.96                                      | 2.58                    |
| Pruning scissors                 | kg             | 0.30     | 1825.00            | 48.96                                      | 0.80                    |
| Mechanized backpack brush-cutter | kg             | 12.00    | 3650.00            | 48.96                                      | 19.32                   |
| <sup>a</sup> Other tools         | kg             | 10.00    | 1825.00            | 48.96                                      | 32.19                   |
| Trellis                          | number         | 1.00     | 5475.00            | 544,878.03                                 | 11,942.53               |
| <i>Total Indirect Energy</i>     |                |          |                    |  | <i>12,027.01</i>        |
| <b>Total Energy Inputs</b>       |                |          |                    |  | <b>30,542.51</b>        |

<sup>a</sup>Refers to the sum of hand tools used in the production process

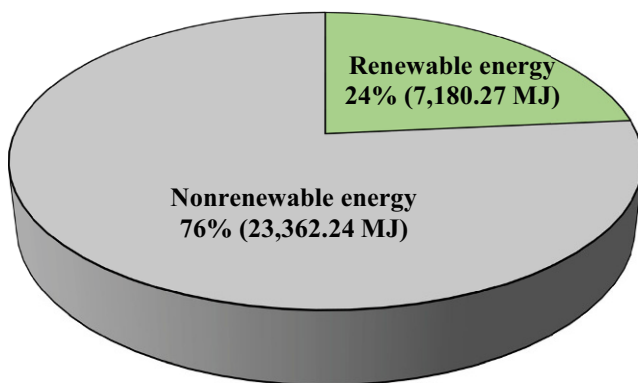
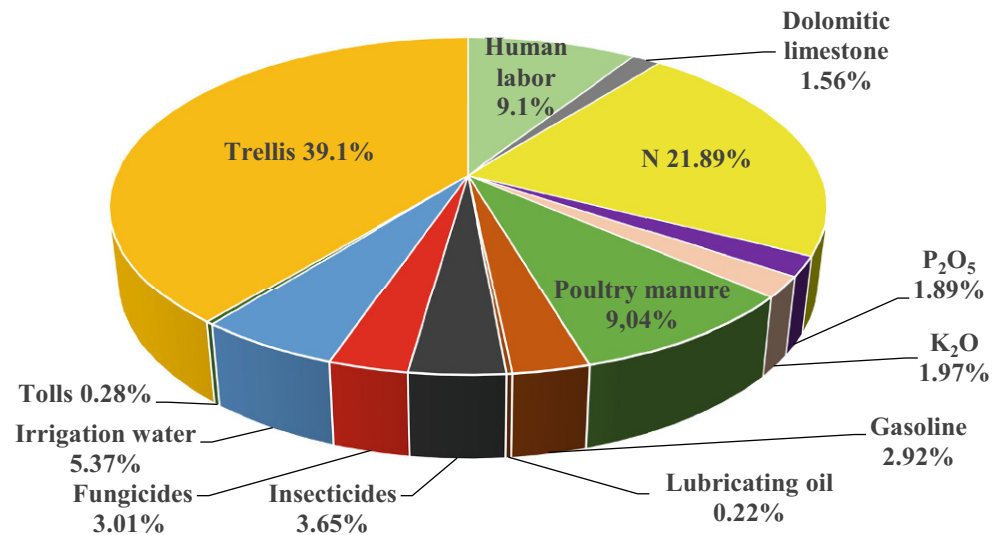
a characteristic of family farming in the state of Espírito Santo/Brazil. When evaluating the energy flows in viticulture in the region of Thrace, Turkey, Akdemir (2022) found that the input of fossil fuels accounted for 26.29% of the total input with 3192.78 MJ. For the same energy input, Kamari et al. (2021), when evaluating energy flows in grape production in Eyvan County, Iran, found that fossil fuels accounted for 14.98% (4247.59 MJ) of the total entries. These data indicate that viticulture in the region studied, regarding energy consumption ha<sup>-1</sup> (MJ), has a performance up to 4.40 times better than that achieved with the input of fossil fuels.

Santos et al. (2021) reported that viticulture practiced in tropical regions is more dependent on pesticides, especially fungicides. These factors add an addition demand, increase dependence on external inputs, and cause environmental damage. Tian et al. (2019) evaluated the energy consumption in grape production in two annual harvests in the Guangxi region of southern China and found similar results. Chemical fertilizers and pesticides accounted for 41.65 and 25.20% of the total entries in the first crop and 39.29 and 25.66% in the second, respectively. However, in the present study, fungicides and insecticides contributed 3.01% (1114.40 MJ) and 3.65% (920.00 MJ), respectively, of the total input energy, for a total of 6.6% (2034.40 MJ)

(Table 3 and Fig. 1). This value agrees with that identified by Malwe et al. (2022), who evaluated the energy balance for grape production in the Sangli region of India, these researchers found a participation rate of 7.96% (3127.98 MJ) for agricultural pesticides in production systems. Namdari et al. (2021), when evaluating the efficiency of energy use in grape production in the province of Hamadan, western Iran, found that the participation of pesticides in the total energy intake was only 0.50% (170.40 MJ ha<sup>-1</sup>). The authors emphasize that despite this small rate, there is still misuse of these inputs by farmers and that it is fully possible to save energy through these inputs. They also add that the misuse of these inputs can cause adverse health effects in the short term, as well as chronic adverse effects that may occur months or years after exposure.

Water and energy are the main inputs of agricultural production systems. The efficient use of these resources is essential for better productivity and economic competitiveness of agriculture, as well as for achieving satisfactory levels of sustainability. Modern irrigation systems are, on the one hand, highly efficient in terms of water use but, on the other hand, demand high energy input (Correa-Cano et al. 2022; Ahmad and Khan 2017). Khoshroo et al. (2013) evaluated energy consumption in grape production in Ilan Province, Iran. The authors observed that the energy

**Fig. 1** Percentage shares of energy inputs per hectare of cultivation in viticulture practiced in the hot climate region of the state of Espírito Santo/Brazil



**Fig. 2** Percentage shares of renewable and nonrenewable energy input per hectare of cultivation in viticulture practiced in the hot climate region of the state of Espírito Santo/Brazil

inputs with the highest participation rates were irrigation water (37.00%), electricity (28.00%), chemical pesticides (14.00%) and manure (11.00%).

Baran et al. (2017), when evaluating energy consumption in organic grape production in the province of Adi Barman, Turkey, observed that the most expressive inputs were machines and equipment (163,430.00 MJ ha<sup>-1</sup>) and irrigation water (24,875.00 MJ ha<sup>-1</sup>). In the present study, the irrigation water input, in three of the evaluated properties, was pressurized via an electrically driven motor pump to a reservoir at a higher elevation, which enabled gravity irrigation to occur. In the other eight farms studied in the region, a spring at a higher elevation than the orchards enabled naturally-occurring, gravity-driven pressurization. Therefore, the electric energy of the settlement was embedded in the composition of the irrigation water input (Turco et al. 2018; Timsina et al. 2022). In addition, sustainable irrigation management was adopted for all properties by estimating evapotranspiration according to local minimum and maximum

temperatures (Hargreaves–Samani) (Althoff et al. 2019). Therefore, this intake represented only 5.37% of the total intake (Fig. 1), with an energy value of 1640.21 MJ (Table 3).

Indirect energy accounted for 39.38% (12,027.10 MJ) of the total energy entering the system. The trellis was the major energy input in the evaluated systems, with 39.10% (11,942.53 MJ) of the total energy input and 99.30% of the total indirect energy. The equivalent energy cost for the trellis was 1.19 MJ m<sup>-2</sup> for construction. Several studies that analyzed energy flows in viticulture on a global scale (Baran et al. 2017; Khoshroo et al. 2018; Mohseni et al. 2019; Kamari et al. 2021; Akdemir 2022), did not consider the constructive aspects of the supporting structures for plants. However, an analysis of the role of trellises in the composition of energy inputs in this study is highly relevant. Thus, it is of fundamental importance that in future evaluations, as in the present study, the energy inputs inherent to the construction materials, their respective energy depreciation, the direct energy involved in its various forms, and all the necessary energy inputs for the construction of the support structure of the plants are considered for the structure, trellis, espalier, “Y” or any other entity that meets the local need. Furthermore, when the energy cost inherent to the supporting structure of the plants is not considered, an overestimation of the energy sustainability indices of the evaluated systems may occur.

Renewable energy (human labor, manure and irrigation water) accounted for 24.00% (7180.27 MJ) of the total energy that entered the conversion system. Nonrenewable energy (chemical fertilizers, fossil fuels, pesticides, trellis and equipments) accounted for 76.00% (23,362.24 MJ) of entries (Fig. 2). This also indicates a dependence of viticulture on nonrenewable energy sources, which is very pronounced due to the “Trellis” energy input in the present

**Table 4** Energy outputs for viticulture in the warm climate region of the state of Espírito Santo/Brazil, per hectare of cultivation

| Available Energy (outputs)    | Unit | Quantity  | Equivalent Energy (MJ Unit <sup>-1</sup> ) | Energy value (MJ) |
|-------------------------------|------|-----------|--|-------------------|
| Ripe grape                    | kg   | 16,336.60 | 11.80                                      | 192,771.88        |
| Pruning residues of the vines | kg   | 2780.00   | 19.00                                      | 52,820.00         |
| <i>Total Departures</i>       |      |           |  | 245,591.88        |

**Table 5** Energy indices, respective values and units, for viticulture activity in the warm climate region of the state of Espírito Santo/Brazil, per hectare of cultivation

| Energy Index                  | Value      | Unit                |
|-------------------------------|------------|---------------------|
| Total energy efficiency (TEE) | 8.04       | –                   |
| Grape energy efficiency (GEE) | 6.31       | –                   |
| Grape energy conversion (GEC) | 0.53       | Kg MJ <sup>-1</sup> |
| Grape specific energy (GSE)   | 1.87       | MJ kg <sup>-1</sup> |
| Net available energy (NAE)    | 215,049.37 | MJ                  |

study. The dependence of viticulture on nonrenewable sources is a trend observed very frequently in the literature. Similar behaviors to the present study were observed for of renewable and nonrenewable energy: 26.79 and 73.21%; 6.12 and 93.88%; 22.47 and 77.53%; 37.00 and 63.00%; and 8.00 and 92.00% in Simsek et al. (2022), Akdemir (2022), Kamari et al. (2021), Khoshroo et al. (2018) and Tian et al. (2018), respectively.

To reduce viticulture's dependence on nonrenewable energy sources, it is necessary to increase the use of renewable energy sources as a proven alternative for the conservation of natural resources and integrate renewable energy into production systems, regardless of location or energy transmission infrastructure. This is a great opportunity not only to reduce energy and carbon costs, but also to reduce dependence on external inputs, improve the standard of living of rural communities, and increase food security (Burg et al. 2016; Robinson 2021; Pestisha et al. 2023).

The energy outputs, consolidated in Table 4, were 245,591.88 MJ. The average grapevine yield for the evaluated systems was 16,336.60 kg ha<sup>-1</sup>.

The energy output for ripe grapes corresponded to 78.00% (192,771.88 MJ) of the total output. González et al. (2015) reported that in cultivars of the species *Vitis labrusca L.*, the generation of pruning residues is approximately 2780.00 kg ha<sup>-1</sup>. These residues corresponded to 22.00% (52,820.00 MJ) of the outputs in the conversion systems (Table 4).

The net available energy (NAE) was 215,049.37 MJ. The total energy efficiency (TEE), considering all system outputs, was 8.04 (Table 5). This value indicates that the ratio between the sum of the total input energies and the output energies of the conversion system is greater than one unit. This value means that every 1 MJ of energy supplied to the system has the capacity to convert into 8.04 MJ. According to Khoshroo et al. (2018) and Turco et al. (2018),

considering the energy efficiency indices as an indicator of sustainability, from the energy point of view, the systems evaluated are sustainable. The energy efficiency of the present study was higher than that found for viticultural systems by Kargwal et al. (2022) (4.95); Malwe et al. (2022) (5.92); Mohseni et al. (2019) (5.75); Vafabakhsh and Mohammadzadeh (2019) (0.98) and Baran et al. (2017) (6.57).

The grape energy conversion (GEC) was 0.53 kg MJ<sup>-1</sup>, which means that for each MJ of energy invested in the conversion systems, 0.53 kg of ripe grapes were obtained (Table 5). In contrast, the grape specific energy (GSE) was 1.87 MJ kg<sup>-1</sup>. This result indicates that for the conversion of one kilogram of ripe grapes, an energy investment of 1.87 MJ is required in the evaluated systems. Similar results were reported by Kamari et al. (2021) in vine orchards in Iran (0.67 kg MJ<sup>-1</sup>). There is a trend that the energy indices found for viticulture in the study region are improved from the 5<sup>th</sup> year of production, since the crops are still young (3<sup>rd</sup> year of production) and therefore have average productivity (16,336.60 kg ha<sup>-1</sup>) below the state average (18,000 kg ha<sup>-1</sup>) (Pedeag 3 2015).

Regarding the grape energy efficiency (GEE), an index of 6.31 was found. Following the above premises, the system would already be sustainable. Due to the large amounts of pruning residues, the vine cultivation system requires the adoption of adequate and effective management of this type of residue (Maj et al. 2022). Observations indicate that when value is added to the waste from the production process, energy efficiency increased by 33.00%, with a TEE of 8.04. The pruning residues can and should be used in the grape production process, as well as in other activities of the properties, constituting, therefore, an economic option for the family farmer. Thus, pruning residues are a useful and economical input and should also be accounted for as available energy. This proposition agrees with the results obtained by Nunes et al. (2021), Souza et al. (2009) and Santos and Lucas Júnior (2004). These authors state that every production process generates waste and that all waste stores some energy. Therefore, production systems can convert this waste into energy, reduce its production cost and function in an energy-balanced manner, and improve the sustainability levels of agroecosystems, such as the agroecosystems evaluated in this study.

## Conclusions

Of the total energy that enters the energy conversion systems (vineyards), 60.62% (18,515.50 MJ) refers to direct energy. In the composition of this input, nitrogen fertilizer was more relevant, with 21.89% (6685.60 MJ). Indirect energy accounted for 39.38% (12,027.01 MJ) of the total energy. The trellis was the major energy input, with 39.10% (11,942.53 MJ) of the total energy input and 99.30% of the total indirect energy. The equivalent energy cost for the trellis was 1.19 MJ m<sup>-2</sup> for construction. Renewable energy (human labor, manure and irrigation water) accounted for 24.00% (7180.27 MJ) of the total energy input. Non-renewable energy (chemical fertilizers, fossil fuels, crop protection products, trellis and equipment) totaled 76.00% (23,362.24 MJ), in trellis the input that cost the most energy. The total energy output was 245,591.88 MJ, and ripe grapes and vine pruning residues corresponded to 78.00% (192,771.88 MJ) and 22.00% (52,820.00 MJ), respectively, of the outputs. The total energy efficiency (TEE), grape energy efficiency (GEE) and grape energy conversion (GEC) were 8.04; 6.31 and 0.53 kg MJ<sup>-1</sup>, respectively. The total grape specific energy (GSE) and net available energy (NAE) were 1.87 MJ kg<sup>-1</sup> and 215,049.37 MJ, respectively. When considering grape production in the warm region of Espírito Santo, the system was sustainable, in which each MJ invested was converted into 6.31 MJ in product (grape). However, when considering the energy value added to the vine pruning waste, there was a 33.00% increase in efficiency, thus 1 MJ was converted into 8.04 MJ.

**Acknowledgements** To the National Council for Scientific and Technological Development (CNPq/Brazil), the State Secretariat for Agriculture, Supply, Aquaculture and Fisheries (SEAG/ES/Brazil) and the Espírito Santo Research and Innovation Support Foundation (FAPES/Brazil) for their support in the research projects. To the winegrowers of the warm region of the state of Espírito Santo/Brazil for making experimental areas and information available.

**Funding** The work was funded by the State Secretariat for Agriculture, Supply, Aquaculture and Fisheries (SEAG/ES/Brazil) through the Espírito Santo Research and Innovation Support Foundation (FAPES/Brazil). There was also funding from the National Council for Scientific and Technological Development—CNPq/Brazil.

**Author Contribution** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Cássio Vinícius de Souza, José Aires Ventura, Jacimar Luis de Souza, Diolina Moura Silva and Carlos Alberto Sangali de Mattos. The first draft of the manuscript was written by Cássio Vinícius de Souza and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Data Availability** The datasets generated during and/or analyzed during the current study are not publicly available due to reasons of data protection.

**Conflict of interest** C.V. de Souza, J.A. Ventura, J.L. de Souza, D.M. Silva and C.A.S. de Mattos declare that they have no competing interests.

## References

- Ahmad A, Khan S (2017) Water and energy scarcity for agriculture: is irrigation modernization the answer? *Irrig Drain* 66(1):34–44. <https://doi.org/10.1002/ird.2021>
- Ahmadbeyki A, Ghahderijani M, Borghae A, Bakhoda H (2023) Energy use and environmental impacts analysis of greenhouse crops production using life cycle assessment approach: a case study of cucumber and tomato from Tehran province, Iran. *Energy Rep* 9:988–999. <https://doi.org/10.1016/j.egy.2022.11.205>
- Akdemir S (2022) Determination of energy balance in grape production for wine in thrace region. *Erwerbs-Obstbau* 64(Suppl 1):103–111. <https://doi.org/10.1007/s10341-022-00730-6>
- Althoff D, Santos RA, Bazame HC, Cunha FF, Filgueiras R (2019) Improvement of Hargreaves–Samani reference evapotranspiration estimates with local calibration. *Water* 11:2272. <https://doi.org/10.3390/w11112272>
- Aseffe JAM, Jaén RL, Olivaruiz LO, González AM, Lora EES (2019) Análisis do ciclo de vida del aprovechamiento energético de los residuos (tusa) de la cosecha de maíz (*Zea mays*) na província de Los Ríos, Ecuador. *Tecnol Quím* 39(3):655–672
- Baran MF, Lüle F, Gökdoğan O (2017) Energy input-output analysis of organic grape production: a case study from Adiyaman Province. *Erwerbs-Obstbau* 59(4):275–279. <https://doi.org/10.1007/s10341-017-0322-1>
- Baran MF, Eliçin AK, Bellitürk K, Çelik A (2022) Energy balance and greenhouse gas (GHG) emissions of Sauceboat Pepper (*Capsicum annum* L.) production in Türkiye. *Int J Agric Environ Food Sci* 6(4):605–613. <https://doi.org/10.31015/jaefs.2022.4.14>
- Bersch AP, Brun EJ, Pereira FA, Silva DA, Barba YR, Dorini Júnior JR (2018) Caracterização energética da madeira de três materiais genéticos de *Eucalyptus* Sp. *RF* 48(1):87–92. <https://doi.org/10.5380/rf.v48i1.51673>
- Burg P, Ludín D, Rutkowski K, Krakowiak-Bal A, Trávníček P, Zemánek P, Turan J, Višacki V (2016) Calorific evaluation and energy potential of grape pomace. *Int Agrophys* 30(2):261–265. <https://doi.org/10.1515/intag-2015-0082>
- Campos I, Marín-González E, Luz G, Barroso J, Oliveira N (2019) Renewable energy prosumers in mediterranean viticulture social–ecological systems. *Sustainability* 11(23):6781. <https://doi.org/10.3390/su11236781>
- Correa-Cano ME, Salmoral S, Rey D, Knox JW, Graves A, Melo O, Foster W, Naranjo L, Zegarra E, Johnson C, Viteri-Salazar O, Yan X (2022) A novel modelling toolkit for unpacking the water-energy-food-environment (WEFE) nexus of agricultural development. *Renew Sustain Energy Rev* 159:112182. <https://doi.org/10.1016/j.rser.2022.112182>
- Elhami B, Raini MGN, Soheili-Fard F (2019) Energy and environmental indices through life cycle assessment of raisin production: A case study (Kohgiluyeh and Boyer-Ahmad Province, Iran). *Renew Energy* 141:507–515. <https://doi.org/10.1016/j.renene.2019.04.034>
- González AFR, Salcedo AVR, Velasco F (2015) Características energéticas de combustibles densificados de residuos de la uva isabella (*Vitis labrusca* L.). *Rev Mutis* 5(2):5–15. <https://doi.org/10.21789/22561498.1069>
- Pedeag 3 (2015) - Plano estratégico de desenvolvimento da agricultura capixaba PEDEAG 3 2015–2030: Espírito Santo sustentável. Governo do Estado do Espírito Santo, Vitória, 206 p.



- Hamedani SR, Keyhane A, Alimardani R (2011) Energy use patterns and econometric models of grape production in Hamadan province of Iran. *Energy* 6(11):6345–6351. <https://doi.org/10.1016/j.energy.2011.09.041>
- Kaab A, Sharifi M, Mobli H, Nabavi-Pelesaraei A, Chau KW (2019) Combined life cycle assessment and artificial intelligence for prediction of output energy and environmental impacts of sugarcane production. *Sci Total Environ* 664:1005–1019. <https://doi.org/10.1016/j.scitotenv.2019.02.004>
- Kamari F, Ghamary B, Azizpanah A (2021) Determination and Evaluation of energy consumption for grape production in Eyvan county (Ilam province). *Agric Eng Int CIGR J* 23(03):173–181
- Kargwal R, Yadvika AK, Garg MK, Chanakaewsomboon I (2022) A review on global energy use patterns in major crop production systems. *Environ Sci Adv* 1:662679. <https://doi.org/10.1039/D2VA00126H>
- Karimi M, Moghaddam H (2018) On-farm energy flow in grape orchards. *J Saudi Soc Agric Sci* 17(2):191–194. <https://doi.org/10.1016/j.jssas.2016.04.002>
- Keshavarz Afshar R, Alipour A, Hashemi M, Jovini MA, Pimentel D (2013) Energy inputs-yield relationship and sensitivity analysis of pistachio (*Pistacia vera* L.) production in Markazi Region of Iran. *Span J Agric Res* 11(3):661–669. <https://doi.org/10.5424/sjar/2013113-3877>
- Khoshroo A, Mulwa R, Emrouznejad A, Arabi B (2013) A non-parametric Data Envelopment Analysis approach for improving energy efficiency of grape production. *Energy* 63:189–194. <https://doi.org/10.1016/j.energy.2013.09.021>
- Khoshroo A, Emrouznejad A, Ghaffarizadeh A, Kasraei M, Omid M (2018) Sensitivity analysis of energy inputs in crop production using artificial neural networks. *J Clean Prod* 197(1):992–998. <https://doi.org/10.1016/j.jclepro.2018.05.249>
- Maj G, Klimek K, Kaplan M, Wrzesinska-Jedrusiak E (2022) Using wood-based waste from grapevine cultivation for energy purposes. *Energies* 15(3):890. <https://doi.org/10.3390/en15030890>
- Malwe PD, Gawali B, Deshpande M, Panchal H, Darade P (2022) Energy nexus for grapes production: a case study of Sangli region in India. *Energy Nexus* 8(4):100145. <https://doi.org/10.1016/j.nexus.2022.100145>
- Matassa S, Boeckx P, Boere J, Erisman JW, Guo M, Manzo R, Meerburg F, Papirio S, Pikaar I, Rabaey K, Rousseau D, Schnoor J, Smith P, Smolders E, Wuertz S, Verstraete W (2023) How can we possibly resolve the planet's nitrogen dilemma? *Microb Biotechnol* 16:15–27. <https://doi.org/10.1111/1751-7915.14159>
- Menezes Neto JB, Mattos LS, Caporal FR (2018) Análise da dinâmica energética de agroecossistemas. *Exten Rur* 25(3):73–88. <https://doi.org/10.5902/2318179632691>
- Mercenaro L, Nieddu G, Pulina P, Porqueddu C (2014) Sustainable management of an intercropped Mediterranean Vineyard. *Agric Ecosyst Environ* 192:95–104. <https://doi.org/10.1016/j.agee.2014.04.005>
- Mohseni P, Borghae AM, Khanali M (2019) Energy consumption analysis and environmental impact assessment of grape production in hazavah region of Arak City. *J Agric Mach* 9(1):177–193. <https://doi.org/10.22067/jam.v9i1.67645>
- Moraes AJR, Silva ESA, Almeida EM, Mezenes JEA (2018) Avaliação dos impactos econômico, social e ambiental do cultivo da pimenteira-do-reino com tutor vivo de gliricídia no estado do Pará. *Braz J Dev* 4(07):3696–3715
- Namdari M, Mobtaker HG, Rasouli M (2021) Using DEA models to measure energy efficiency of grape production. *Int J Agric Manag Dev* 11(4):485–493
- Nouri-khjelagh R, Sefdkouhi MAG, Khoshravesh M (2023) Evaluation of energy indices and greenhouse gas emissions in major horticultural crops and paddy crops in Tajan plain. *Appl Water Sci* 13:39. <https://doi.org/10.1007/s13201-022-01840-y>
- Nunes LJR, Rodrigues AM, Matias JCO, Ferraz AI, Rodrigues AC (2021) Production of biochar from vine pruning: waste recovery in the wine industry. *Agriculture* 11(6):489. <https://doi.org/10.3390/agriculture11060489>
- Palmay P, Medina C, Vargas K (2021) Piroloxidación de plásticos de invernadero para recuperar ceras líquidas útiles para refinación. *Cienc Lat Rev Cient Multidiscip* 5(3):2463–2476. [https://doi.org/10.37811/cl\\_rcm.v5i3.464](https://doi.org/10.37811/cl_rcm.v5i3.464)
- Paris B, Vadorou F, Balafoutis AT, Vaiopoulos K, Kyriakarakos G, Manolakis D, Papadakis G (2022) Energy use in open-field agriculture in the EU: a critical review recommending energy efficiency measures and renewable energy sources adoption. *Renew Sustain Energy Rev* 158:112098. <https://doi.org/10.1016/j.rser.2022.112098>
- Pestisha A, Gabnai Z, Chalgybayeva A, Lengyel P, Bai A (2023) On-Farm renewable energy systems: a systematic review. *Energies* 16(2):862. <https://doi.org/10.3390/en16020862>
- Rahmani A, Parashkoochi MG, Zamani DM (2022) Sustainability of environmental impacts and life cycle energy and economic analysis for different methods of grape and olive production. *Energy Rep* 8(17):2778–2792. <https://doi.org/10.1016/j.egyr.2022.01.197>
- Robertson GP, Vitousek PM (2009) Nitrogen in agriculture: Balancing the cost of an essential resource. *Annu Rev Environ Resour* 34:97–125. <https://doi.org/10.1146/annurev.enviro.032108.105046>
- Robinson D (2021) Rural food and wine tourism in Canada's south okanagan valley: transformations for food sovereignty? *Sustainability* 13(4):1808. <https://doi.org/10.3390/su13041808>
- Santos TMB, Lucas Júnior J (2004) Balanço energético em galpão de frangos de corte. *Eng Agríc* 24(1):25–36. <https://doi.org/10.1590/S0100-69162004000100004>
- Santos AO, Santos NAP, Moreira CA, Lima MA, Lino ACL (2021) Development and test of a confining and recycling sprayer for viticulture. *Rev Bras Frutic* 43(6):1–13
- Seflek AY, Acaroglu M, Yalçın Dokumaci K, Özbek O, Haciseferoğullari H (2018) Energy balance for camelina under Turkish Conditions. *J Agric Fac Gaziosmanpasa Univ* 35(2):134–140
- Silva PHF, Gasparotto F, Emanuelli IP, Schimidt Filho E, Yamaguchi NU (2019) Análise de ciclo de vida da viticultura: estado da arte. *Rev Valore* 4:289–301
- Silva PRS, Araújo MKC, Ramos CRG, Santos RSS, Silva MAP (2020) Análise energética e econômica da implantação da cultura da pitaya em manejo orgânico no município de Tomé-Açu/PA. *EngAgric* 35(4):616–626. <https://doi.org/10.17224/EnergAgric.2020v35n4p616-626>
- Simsek E, Oguz HI, Gökdogan O (2022) Energy use efficiency of grape production in vineyard areas of Nevşehir Province in Turkey. *Erwerbs-Obstbau* 64(1):113–118. <https://doi.org/10.1007/s10341-022-00707-5>
- Soltani S, Mosavi SH, Saghayan SH, Azhdari S, Alamdarlo HN, Khalilian S (2023) Climate change and energy use efficiency in arid and semiarid agricultural areas: A case study of Hamadan-Bahar plain in Iran. *Energy* 268:126553. <https://doi.org/10.1016/j.energy.2022.126553>
- Souza CV, Campos AT, Bueno OC, Silva EB (2009) Análise energética em sistema de produção de suínos com aproveitamento dos dejetos como biofertilizante em pastagem. *Eng Agríc* 29(4):547–557. <https://doi.org/10.1590/S0100-69162009000400005>
- Steinmann ZJN, Huijbregts MAJ, Reijnders L (2019) How to define the quality of materials in a circular economy? *Resour Conserv Recycl* 141:362–363. <https://doi.org/10.1016/j.resconrec.2018.10.040>
- Theron H, Hunted JJ (2022) Mitigation and adaptation practices to the impact of climate change on wine grape production, with special reference to the South African context. *SAJEV* 43(1):10–25. <https://doi.org/10.21548/43-1-4735>

- Tian D, Zhang M, Wei X, Wang J, Um W, Feng J (2018) GIS-based energy consumption and spatial variation of protected grape cultivation in China. *Sustainability* 10(9):3248. <https://doi.org/10.3390/su10093248>
- Tian D, Zhang M, Xiong C, Um W, Feng J (2019) Measuring the energy consumption and energy efficiency in two-harvest-a-year grape cultivation. *Energy* 189:116258. <https://doi.org/10.1016/j.energy.2019.116258>
- Timsina J, Dutta S, Devkota KP, Chakraborty S, Neupane RK, Bista S, Amgain LP, Majumdar K (2022) Assessment of nutrient management in major cereals: Yield prediction, energy-use efficiency and greenhouse gas emission. *Curr Res Environ Sustain* 4:100147. <https://doi.org/10.1016/j.crsust.2022.100147>
- Turco PHN, Esperancini MST, Bueno OC, Oliveira MDM (2018) Balanço energético dos sistemas de produção de café convencional e irrigado. *EnergAgric* 33(1):73–80. <https://doi.org/10.17224/EnergAgric.2018v33n1p73-80>
- Uzun T, Baran MF (2022) Energy input–output analysis of grape (*Vitis vinifera* L.) production in Turkey. *Erwerbs-Obstbau* 64(1):95–102. <https://doi.org/10.1007/s10341-022-00670-1>
- Vafabakhsh J, Mohammadzadeh A (2019) Energy flow and GHG emissions in major field and horticultural crop production systems (case study: Sharif Abad Plain). *J Agroecol* 11(2):365–382. <https://doi.org/10.22067/jag.v11i2.81742>
- Zamboni I, Colantoni A, Cecchini M, Mosconi EM (2018) Rethinking sustainability within the viticulture realities integrating economy, landscape and energy. *Sustainability* 10(2):320. <https://doi.org/10.3390/su10020320>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.