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*Original*
Harvesting system sustainability in Mediterranean olive cultivation / Bernardi, B., Falcone, G., Stillitano, T., Benalia, S., Strano, A., Bacenetti, J., De Luca, A.I.. - In: SCIENCE OF THE TOTAL ENVIRONMENT. - ISSN 0048-9697. - 625:(2018), pp. 1446-1458. [10.1016/j.scitotenv.2018.01.005]

*Published*
DOI: http://doi.org/10.1016/j.scitotenv.2018.01.005

Harvesting system sustainability in Mediterranean olive cultivation
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https://doi.org/10.1016/j.scitotenv.2018.01.005

## Abstract

The mechanization of farming operation plays an important role in improving the profitability of the agricultural sector by increasing work productivity and reducing production costs. However, the new challenges of agriculture also include the environmental issues. The choice between different alternatives to perform a determined agricultural practice should be based on reliable information, considering technical, economic and environmental aspects. Olive growing represents the most important agricultural production in the Mediterranean Basin and its mechanization, particularly harvesting, could have major impacts on the sustainability of this production. This study aims at assessing various olive-harvesting scenarios, while considering technical, economic and environmental aspects in order to build a beta version of the "olive-harvesting database". The proposed methodology called "modular approach" could represent a useful tool to apply in unitary process assessment in order to obtain a comprehensive database of the diverse agricultural operations. The methodology was based on Life Cycle Assessment and production cost analysis. Technical performance evaluation showed that the recorded work capacities varied between 5 tons of harvested olives per day when employing mechanical harvest aids and 18 tons per day when employing trunk shakers. The economic evaluation highlighted that the harvesting costs are variable as a function of the given cost type (costs per hour, costs per kg of harvested olives and costs per hectare). The LCA revealed that mechanically aided techniques were the most sustainable ones when the functional unit is considered as one harvesting hour, although this FU is not the most suitable unit for choosing the best environmental solution. The surface and production mass units are more appropriate FUs in comparative studies, although they are strictly linked to the "work capacity". A significant variation in the environmental performances depended on the FUs and on the average yields when the FU represented one kg of harvested olives.

***Keywords:*** Mechanical harvesting; olive orchard; work productivity; economic sustainability; life cycle assessment (LCA); environmental impact.

## 1 Introduction

Growing olives has a productive function that is associated with hydrological and landscape preservation (Loumou & Giourga, 2003), and it represents a key sector for the whole Mediterranean Basin. The Calabria region (Italy) is home to over 183,000 hectares of olive orchards, and it produces approximately 890,000 tons of olive oil (ISTAT, 2016). The co-existence of traditional olive orchards with a very low planting density and intensive new groves consisting of up to 600 plants/ha characterizes this considerable patrimony. The predominance of small and medium-sized enterprises on one hand and farm area fragmentation on the other hand primarily characterize these olive orchards, leading to a low production of extra virgin olive oil. However, the productive system should aim to enhance high-quality products, which may be labelled with the newly obtained Protected Geographical Indication certification, “IGP Olio di Calabria”. In this situation, aided and mechanical harvesting can play an important role in improving olive grove profitability. This agricultural practice constitutes one of the most influential approaches in relation to olive oil production costs (Cicek, 2011), since it absorbs 50% of the product value alone due to the continuous increase in labour costs. This situation is additionally aggravated by the scarcity of labourers (Bentaher et al., 2013). The employment of mechanical harvest aids or mechanical beaters has increased work productivity by 50% compared to manual harvesting using poling sticks; similarly, trunk and canopy shakers have significantly improved the field working capacity of traditional olive orchards (Rallo et al., 2013; Sola-Guirado et al., 2014). Several studies about olive growth have been performed to focus on technical aspects such as machine functioning; e.g., Blanco-Roldán et al. (2009) report the effects of the trunk shaker duration and repetitions on the removal efficacy. Leone et al.

(2015) studied the vibration frequency, acceleration and duration when using a trunk shaker. Other studies addressed the rational organization of harvesting sites; Famiani et al. (2014) evaluated the possibility of mechanizing the olive harvest in groves consisting of old and very large trees; Ferguson et al. (2010) investigated the harvest of California table and oil olives. In addition, the aspects related to the effects of the harvest on the olive oil quality were deepened (Dag et al., 2011; Zipori et al., 2014).

The mechanization of agricultural production processes should also be validated from an environmental point of view, preferably by considering all the inputs and outputs connected to the implemented technology. A methodology that is well-suited for the evaluation of various technological solutions is the life cycle assessment (LCA) (ISO 14040, 2006). This method allows for the valuation of all the inputs and outputs associated with the life of the product or the process (Guinée, 2002; Horne et al., 2009). Agriculture represents one of most highly polluting economic sectors, producing approximately 10% of European emissions of greenhouse gases (EEA, 2014) and approximately 90% of acidifying pollutant emissions and depleting nearly 34% of freshwater resources (EEA, 2012). In particular, the energy use represents the third-highest carbon dioxide equivalent ($CO_2$-eq) emission category in agriculture, with a greenhouse gas (GHG) production in $CO_2$ eq that was equal to 748,853.4 Gg in 2011 (FAOSTAT, 2015a). More specifically, the combustion of gas-diesel oil represents the highest emission source among this impact category, producing 336,519.5 Gg of $CO_2$ eq (FAOSTAT, 2015b). Olive growth measurements cannot dispense with these types of assessments, and, for this reason, several studies were performed in Italy (Martinez et al., 2014; Notarnicola et al., 2013; Rinaldi et al., 2014; Salomone et al., 2010; Salomone et al., 2015; Salomone & Ioppolo, 2012), Spain (Ramos et al., 2000) and Greece (Tsarouhas et al., 2015). Recently, this methodology has been jointly performed with economic (De Gennaro et al., 2012; De Luca et al., 2017; Mohamad et al., 2014; Notarnicola et al. 2003, Notarnicola et al 2004; Pergola et al., 2013a) and social (De Luca et al., 2018) evaluations often using the same methodological framework as the LCA, to achieve an integrated sustainability assessment. According to Salomone et al. (2015), most of this research has focused on comparative studies of the whole olive cultivation or olive milling processes. Much rarer is the use of a partial analysis to deepen the different ways in which a unitary process can be performed. This kind of deepened study has already been addressed for the biomass harvesting (Mirabella et al., 2014; Proto et al., 2017) and an effort to support the data collection of mechanical operations in agriculture was made by Lovarelli et al. (2016) and Lovarelli and Bacenetti (2017). In particular, olive cultivation represents a production process that is well-suited to mechanical innovation, especially for harvesting, and thus, the use of an LCA modular approach could be useful for the evaluation of different technical solutions (Bacenetti et al., 2015; Buxmann et al., 2009; Cerutti et al., 2014; Jungbluth et al., 2000; Navarro et al., 2017; Rebitzer, 2005).

Although harvesting is one of the most time and production-consuming parts of the operation within the whole olive production process, there is a lack of knowledge regarding its environmental impact, and, in particular, a lack of knowledge concerning the different olive harvesting techniques. For this reason, a comparative assessment combined with a technical and economic analysis could be useful for defining the technical efficiency, cost effectiveness and environmental sustainability of the different harvesting solutions.

In accounting for the above reported considerations, the aim of this study is twofold as follows: I) to evaluate the technical efficiency of various harvesting scenarios, while also assessing their influence on the resulting oil quality; and II) to define the different environmental and economic performances of the different working scenarios when considering the harvesting module as a stand-alone life cycle to make the obtained results applicable in other contexts.

## 2. Materials and Methods

In order to reach the above-described objectives different methodogical steps were performed. First, technical performances, expressed in terms of work capacity and productivity, of different harvesting scenarios, considering harvesting equipement and site organization, were evaluated. This was a propaedeutical step for the following economic and environmental assessments, performed respectively, using cost production and Life Cycle Assessment methodologies. In order to stress the usefulness of the results, further simulations were achieved by scaling the data in two different dimensions considering two alternative Functional Units (FUs): one ha of harvested area (1 ha) and one kg of harvested product (1 kg).

### *2.1 Orchard features*

Experimental trials have been conducted in *Olea europea* L. cv. Carolea orchards for three years. This variety is the oldest and the most widespread in Calabria, thanks to its adaptability to diverse soil and microclimatic conditions, in addition to the over-all uniformity in the physico-chemical characteristics of the oil it produces.

Two types of orchards were considered; the first one included intensive orchards planted with approximately 25-year-old trees (harvesting sites I to IV); however, the second one considered two traditional orchards of over-60-year-old trees (harvesting sites V and VI). These sites are representative of the diverse productive structures found through the Calabrian territory.

At each site, harvesting was performed on trees whose dimensional and technical parameters are reported in table 1. The canopy volume was calculated according to the International Olive Council method (2007), and the quantity of olives per tree, the fruit removal force (FRF) and the FRF/FW (fresh weight) ratio are reported in table 2.

Table 1: Average tree dimensional parameters at the analysed harvesting sites (means ± SE)

Table 2: Olive trees and fruit characteristics at harvest (means ± SE)

### 2.2 *Harvesting scenario organization and equipment*

In scenarios I and II, self-propelled trunk shakers with vibrating heads and a multidirectional configuration of eccentric masses turning at 2200 rpm with 200 bar of oil pressure were used. The labourers consisted in six (6) and five (5) operators, respectively, with one running the harvesting machine while the others were charged with net and olive handling (figure 1).

Figure 1: A self-propelled trunk shaker used in the harvesting operations

In scenario III, a towed radio-controlled shaker with a wrap-around catching frame, a vibrating head of 200 kg and a catching frame diameter of 5.25 m was used (figure 2). Two operators were required, one for driving and controlling the shaker and the other for handling the associated small auxiliary nets.

Figure 2: The towed radio-controlled shaker used in scenario III

Scenario IV involved a motorized, inverted umbrella harvester with a net that had a 7 m diameter, which was known as an Olivspeed Plus GO model (figure 3). Two operators with mechanical pneumatic combs worked to perform the harvest and olive handling.

Figure 3: The Olivspeed used in scenario IV

In scenario V, the harvest was performed using a trunk shaker and a self-propelled windrower with a working width of 2 m and a harvester from the ground with a working width of 2.5 m (figure 4), both of which had substitute nets. The harvesting scenario comprised three operators.

Figure 4: Olive harvesting from the ground in scenario V

All the previous harvesting scenarios were situated on flat terrain, while scenario VI was situated on a sloped (> 20%) and rather inaccessible terrain. Here, the harvest was performed with a small hand-held shaker that was carried by one operator (figure 5), and four other operators were needed for follow-up harvesting with sticks and nets. This type of small shaker is held by a telescopic rod, which is clamped onto the small branches thanks to a U-shaped end connected to an endothermic motor that enables it to generate 2500-3000 strokes per minute.

Figure 5: Small hand-held shaker used in scenario VI

A synthesis of the harvesting scenario composition in terms of equipment and labour is reported in table 3.

Table 3: Synthesis of the harvesting scenario composition

### *2.3 Work productivity determination and olive oil analysis*

To determine the work productivity of the analyzed scenarios, which were calculated and expressed as the quantity from the harvested plants/h/worker, the working time of each phase was recorded. The work capacity and productivity were calculated according to the methodology proposed by the Commission Internationale de l'Organisation Scientifique du Travail en Agriculture (CIOSTA) as described by Bolli & Scotton (1987). After the harvesting trials, a sample of olives from each scenario was collected and micro-milled to analyze the free acidity, peroxide number and spectrophotometric indices of the resulting oils according to CEE 2568/91 and EU 1348/2013 regulations. Moreover, an experienced panel made up of eight judges performed the sensory analysis, according to International Olive Council requirements (IOC, 2015).

A one-way analysis of variance (ANOVA) was performed to evaluate the difference between working time productivity and oil quality according to the harvest working scenario organization. Free R software version 3.1.2 (2014-10-31) was used for data processing.

## 2.4 Economic analysis

From an economic point of view, the analysis focused on the harvesting cost as expressed in terms of the cost per hour (€ $h^{-1}$), cost per unit of product (€ $kg^{-1}$ of harvested olives) and average cost per hectare (€ $ha^{-1}$). The machine hourly cost was determined according to the Miyata (1980) method that accounts for both the machinery operating cost and operator-machine labour cost, as shown in table 4. In the calculation of the machine costs, both the fixed and variable costs were considered. The hourly fixed costs were calculated by dividing the total annual fixed cost (e.g., interest, depreciation, maintenance) by the annual working time, as follows:

$$Hourly\ \ fixed\ \ costs\left(€\,h^{-1}\right)=\frac{Total\ Annual\ Fixed\ Cost\ \left(€\ year^{-1}\right)}{Annual\ \ Working\ \ time\ \left(\ h\ year^{-1}\right)}$$

To calculate the hourly variable costs, both the fuel and oil consumption and the labour costs were estimated. For each harvesting scenario, the primary technical and economical features of the machines and equipements were recorded during field observations (table 5). In I, II and VI, the costs per hour for the nets was included. The latter cost was calculated by considering both fixed costs (depreciation and interest) and the variable cost (the labour cost for the operators involved in net handling). Then, to estimate the total hourly harvesting cost for the different harvesting systems, the machine and net costs were added.

The cost to harvest 1 kg of olives for each analyzed harvesting system was determined by dividing the total hourly cost by the harvesting yield per hour, as follows:

$$Harvesting\ Cost\ per\ kg\ of\ olives\left(€\,kg^{-1}\right)=\frac{Total\ Hourly\ Cost\ \left(€\,h^{-1}\right)}{Harvesting\ \ Yield\ \ per\ \ hour\left(kg\,h^{-1}\right)}$$

Finally, to calculate the average cost per hectare, the harvest cost per kg was multiplied by the harvested yield per hectare, as follows:

$$Harvesting\,Cost\ per\ hectare\left(€\,ha^{-1}\right) = Harvesting\,Cost\ per\ kg\ \left(€\,kg^{-1}\right)\times harvesting\ yield\ per\,hectare\ \left(kg\ ha^{-1}\right)$$

To calculate each cost item, the following assumptions were adopted:

- For the nets, both the purchase price of 400 € $ha^{-1}$ and the economic life of 5 years were considered.
- The work remuneration was evaluated in terms of opportunity cost, and it was equal to the employment of temporary workers for manual (net handling) and mechanical operations (Stillitano et al., 2016) by adopting the current hourly wage (including social security contributions). In particular, for the mechanical operations, qualified workers were employed by considering a compensation of 8.57 € $h^{-1}$, while the salary for the other workers was considered to be equal to 7.14 € $h^{-1}$.
- The machine salvage value was estimated as the demolition material sale (steel and iron) that was equal to 10% of the initial purchase cost.
- The interests on capital goods (machines and nets) were calculated by applying an interest rate equal to 2%.
- An average of 60 working days at 8 hours per day was assumed.

Table 4: Calculation of the machine hourly cost (Miyata, 1980 *modified*)

Table 5: Primary characteristics of the harvesting machines analyzed in this study

## *2.5 Environmental analysis*

To evaluate the potential environmental impacts of the olive harvesting techniques connected to the six studied systems, the LCA method according to the ISO 14040 series (ISO 14040, 2006a; ISO

14044, 2006b) was performed. In particular, in accordance with the ISO framework, the first step of the LCA addressed the definition of the goal and scope.

When considering that the harvesting system choice has negligible consequences on the other field operations, to analyze the environmental consequences of the different harvesting solutions deeply, the system boundaries were limited only to this unitary operation by conducting a partial LCA (figure 6).

Figure 6: System boundary flow chart.

The analyses referred to 1 h of harvesting operations as a functional unit (FU) (table 6). This choice allowed the researchers to make an objective assessment of each individual harvesting scenario. The results could be useful for the scientific community within a “gate to gate” or “cradle to grave” framework of LCA studies on olive oil production. However, to assess the result usefulness, further analyses, were performed using two alternative FUs: the first one consisting in one ha of olive grove (table 7) in order to evaluate the impacts of different harvesting practices in terms of harvested area. This FU is often used for the evaluation of orchard management impacts (Cerutti et al., 2015); while the second FU was represented by 1 kg of harvested olives (table 8), in order to evaluate the impacts related to the unit of the product. This FU is generally used in the product assessment (Cerutti et al., 2015) and it is mandatory for the certification of table olives and olive oil in product category requirements. Thes two units are more appropriate for use as FUs in comparative studies, even though they are strictly linked to the “work capacity”.

In these additional evaluations, the data referred to 1 h of harvesting operations related to the “Work capacity $h^{-1}$” data and the given average production as reported below.

1. Scaling for FU=1 ha of olive grove

$$\left(\frac{Yield\ kg\ ha^{-1}}{Work\ capacity\ kg\ h^{-1}}\right)\times LCI\ results\ \ for\ 1\ h\ of\ \ olive\ harvesting$$

2. Scaling for FU=1 kg of harvested olives

$$\frac{LCI\ results\ \ for\ 1\ h\ of\ \ olive\ harvesting}{Work\ capacity\ kg\ h^{-1}}$$

The data were directly collected from the studied harvesting scenarios through a customized questionnaire that was compiled by the authors.

For the machinery (self-propelled trunk shakers, towed radio-controlled shaker**,** olivspeed and mechanical pneumatic aids, windrower and harvester from the ground**,** hand-held shaker), shed, equipment (operating organs such as the shaking head, the receiving umbrella, the collecting brush) and net production, data were allocated by considering their use in the harvesting operation instead of the useful life of the given tool. The consumption data (diesel and lubricant) were directly measured through the “tanks topping up” technique. Secondary data (diesel and lubricant production, machine production, maintenance and disposal, fuel combustion emissions, metal emissions from the wear and tear of the machines, etc.) were obtained from the Ecoinvent V. 3.3 database (Weidema et al., 2013).

Table 6: Environmental Life Cycle Inventory - LCI (FU 1 h of olive harvesting)

Table 7: Environmental Life Cycle Inventory - LCI (FU 1 ha)

Table 8: Environmental Life Cycle Inventory - LCI (FU 1 kg of harvested olives)

The environmental inventory data were processed using SimaPro 8.1 software (Goedkoop et al., 2013b), and the ReCiPe method at the midpoint (H) and endpoint (H) levels (Goedkoop et al., 2013a) were chosen to process the results from each analyzed scenario. In particular, the results of the characterization using the midpoint method was only being used for the primary FU (1 h of harvesting operation) to evaluate the impacts of different technical solutions from the point of view of the potential environmental effects. These impacts will also be represented with the endpoint method and compared with supplementary FUs, to underline variations due to different FUs according to the environmental damages caused, while being conscious of the results in terms of uncertainty increases (Goedkoop et al., 2013a).

## 3. Results and discussions

### *3.1 Work productivity assessment*

Table 9 reports the work capacity and productivity, calculated in function of the operative time and expressed in terms of the kg $h^{-1}$ and kg $h^{-1}$ $worker^{-1}$, respectively. Moreover, the harvesting efficiency, as expressed as a percentage, was calculated as the ratio between the mechanically harvested quantity of olives and the whole quantity produced by the tree.

Table 9: Calculated work capacity and productivity

In scenarios I and II, an average production of 20 tons $ha^{-1}$ was attained. The work capacity provided by trunk shakers permits us to state that the whole production per hectare can be harvested in one working day with a very high harvesting efficiency. In employing a trunk shaker, Sola-Guirado *et al.* (2014) obtained a mean harvesting efficiency value of 90.5%, while Famiani et al. (2014) obtained a harvesting yield of greater than 70% for ‘Cellina di Nardò', with harvesting working productivities higher than 100 kg of harvested olives $h^{-1}$ $worker^{-1}$ (=1.6 trees $h^{-1}$ $worker^{-1}$).

Michelakis (2002) reports that with this machine, less than 100% of the production is detached, usually from 70% to 90%.

The same considerations can be applied to scenario III, in which the recorded production was 10 tons ha$^{-1}$. Di Vaio et al. (2012) used a similar machine to calculate a mechanical harvesting yield of approximately 97%, and, due to the low number of workers and the reduced time of operation, they reached a very high work productivity equal to an average of 342 kg h$^{-1}$ worker$^{-1}$ for two cultivars. In harvesting scenario IV, the results showed that almost 5 days were needed to harvest the whole production equal to 3.3 tons ha$^{-1}$, while in harvesting scenario VI, two days are needed to harvest the whole production per hectare, corresponding to 5.2 tons. Guirado et al. (2014) used hand-held systems and reported a harvesting efficiency of 98%. Famiani et al. (2014) used a beater + nets and a beater + reversed umbrella, finding a very high harvesting yield (> 95%) with both the beater + nets and the beater + reversed umbrella. The calculated working productivity was approximately 1.3 trees h$^{-1}$ worker$^{-1}$ with the beater + nets; the productivity increased significantly up to approximately 1.7 trees h$^{-1}$ worker$^{-1}$ with the beater + reversed umbrella.

In harvesting scenario V, the employment of the windrower and the harvester from the ground that substituted for manual harvesting and net handling permits a considerable increase in the working productivity. In fact, two hours are enough to harvest the whole production per hectare, which was equal to 4 tons.

The chemical characteristics of olive oils obtained from the studied orchards are reported in table 10. The free acidity expressed as the % of oleic acid, the peroxide value (PV), and the UV absorbencies at 232, 266, 270 and 274 nm of all the investigated olive oils fit within the limits established by the International Olive Council for the extra virgin olive oil category, except for the acidity percentage of the oil obtained from orchard VI. The free acidity and the peroxide value were significantly affected ($p<0.05$) by the harvesting system, probably due to the damages provoked by using sticks for harvesting as well as the harvesting scenario organization, while the other quality indices were not affected. However, it is important to remember that the contact of the olives with the ground that occurs in harvesting scenario V negatively affects the oil quality, particularly from a sensorial point of view. Although, the chemical parameters and the positive attribute (fruity, bitter and hot) median values of the oil obtained from orchard V fit within the limits established by the International Olive Council for the extra virgin olive oil category, the sensorial analysis, performed by a trained panel, downgraded this oil into virgin olive oil category. Indeed, the defect median value was above the limit (1.9 > md=0) as shown in table11. This oil had the so-called *"earthy flavor"* negative attribute, which characterizes the *"oil obtained from olives that have been collected with earth or mud on them and which have not been washed"* (CEE 2568/91). This finding once more confirms that harvesting scenario V is not suitable for extra virgin olive oil production.

Table 10: Chemical characteristics of the analyzed oils

Table 11: Results of the sensory analysis on orchard V olive oil

### ***3.2 Economic assessment***

In terms of the economic assessment, the different harvesting systems showed variable results depending on the considered cost types (costs per hour per kg of olives harvested and cost per hectare).

Figure 7 shows the hourly cost of the different harvest work scenarios analyzed in the study. The results reveal that the V is the harvesting system with the highest cost per hour (72.05 € $h^{-1}$), due to the higher incidence of variable costs related to the fuel consumption. This system also registers the highest fixed costs, which are approximately equal to 45% of the total hourly cost. This finding is primarily due to the depreciation and maintenance costs incurred for the three harvesting machines (shaker-harvested, windrower machine and harvester from the ground). By contrast, scenario IV achieves the best performance in terms of hourly cost, at 20.43 € $h^{-1}$. In this case, the variable costs should be the most influential variable in relation to labour cost representing the 88% of the total cost per hour.Figure 7: Harvesting hourly cost.

Figure 8 illustrates both the cost per kg of harvested olives and the average cost per hectare as incurred using the different analyzed harvesting systems. The mechanical harvesting (scenarios I, II, III and V) and hand-held harvesting techniques (scenarios IV and VI) show the best and the worst economic performances, respectively. The findings are strictly influenced by the diverse harvesting techniques in terms of the employed machine/equipment and labourer number on one hand, and using the obtained yields calculated in function of the operative time and plant productivity in each studied scenario on the other hand. As also argued by Famiani et al. (2014), the unitary cost of harvesting olives can differ according to the hourly machine cost and working productivity of the harvest system. This latter factor depends greatly on the load of the trees and the harvest timing.

The greatest levels of harvesting efficiency achieved in the mechanical harvesting scenarios entailed higher yields, and, therefore, lower costs. In fact, the lowest cost per kg of harvested olives, which corresponded to 0.022 € $kg^{-1}$, was achieved in harvesting scenario III, while the highest value was obtained in scenario IV at 0.24 € $kg^{-1}$, taking into account hourly harvested yields of 1,234.60 and 85.99 kg $h^{-1}$ (table 9), respectively. The variable costs contribute to the highest percentage of the total cost for both systems, which are equal to 88.2% for hand-held harvesting and 50.5% for mechanical harvesting. In mechanical harvesting, scenarios I and II exhibited the highest work capacities (2,726.52 and 2,516.81 kg $h^{-1}$, respectively), and the costs per kg are similar. The highest contribution of the variable costs for these work scenarios was primarily due to the highest share of the labour cost, accounting for more than 60% of the total harvesting cost.

Concerning the average cost per hectare, the V scenario shows the best economic performances, with 153.25 € $ha^{-1}$ compared to 783.94 € $ha^{-1}$ obtained in scenario IV. This wide value range is primarily due to the different amounts of time dedicated to harvesting, which is lower in the V system compared to the IV one.

Several researchers observed that high harvest efficiency values can be reached with mechanical harvesting systems in both traditional (Almeida and Peça, 2012; Bernardi et al., 2016; Sola-Guirado et al., 2014) and intensive orchards (Freixa et al., 2011; Ravetti et al., 2014; Stillitano et al., 2017; Vieri and Sarri, 2010). The results obtained from the intensive scenarios, in which the trunk shaker was employed, were compared to those described by Tous et al. (2014) in Portugal and Spain. These countries obtained similar values for the cost per kg of harvested olives of between 0.09 € and 0.16-0.2 € $kg^{-1}$, but there were higher average costs per hectare with values ranging from 800 € and 1,100 € $ha^{-1}$.

Figure 8: Unit cost per kg of harvested olives and the average cost per hectare.

With regard to traditional orchards, scenario V was the situation in which a greater hourly harvesting yield was achieved, presenting 66% and 74% lower impacts than scenario VI in terms of the cost per kg of harvested olives and the average cost per hectare, respectively. However, as discussed by Castillo-Ruiz et al. (2015), even though the quantity of harvested fruit from the ground is much higher, there is a decrease in the quality. Low quality levels for olive oil negatively affect the possibility of accessing the extra virgin olive oil market price, and thus they diminish the economic profitability of these systems.

The economic findings show the importance of including harvesting technology to reduce the labour costs. In addition, Vieri and Sarri (2010) have widely debated reducing the harvesting costs in terms of optimizing the cost per hour, per hectare and per unit of product. They observed that increasing the working capacity, maintaining constant production levels and using efficient harvester devices could be some of the most important solutions for improving olive cultivation in terms of economic sustainability, supporting the results obtained in the present study.

### *3.3 Environmental assessment*

Regarding the environmental results obtained through the implementation of the Modular LCA method, table 12 shows that when the considered FU is 1 h of work, the harvesting solution with the highest impact is scenario V for all the evaluated impact categories. This impact is due to the mechanization intensity, which implies the following: i) high diesel consumption, ii) high incidence of agricultural machinery construction, maintenance and disposal, iii) shed land occupation and iv) emissions into the air, water and soil due to diesel combustion and tire consumption. The overall best scenario is IV, except for the Ozone depletion, Agricultural land occupation, Urban land occupation and Natural land transformation categories, for which the best performances are achieved in scenario VI. These negative results for scenario IV are attributable to the high incidence of agricultural machinery construction and shed land occupation, in particular due to Olivspeed construction and shelter. Both scenarios IV and VI are characterized by hand-held harvesting techniques, which allow for a lower consumption of fuels but a lower work capacity.

Table 12: Life Cycle Impact Assessment (LCIA) results at the midpoint level (FU 1 h of olive harvesting)

Among the fully mechanized harvesting scenarios, scenario III represents the best solution, with particular thanks to the lower diesel consumption and the absence of nets. Scenarios I and II show similar performances, slightly to the detriment of the second one in which the most powerful tractor generates higher impacts.

The results were also expressed at the endpoint level using the single score representation to quickly compare the environmental performances per FU and between different FUs, highlighting the high influence of the yields on the environmental sustainability of the productive scenarios.

The contribution analysis revealed that fuel production and combustion are the primary contributors to the environmental impacts, excluding scenario VI (figure 9). Fuel contributes an average from 75% to 95% to all the impact categories excluding Freshwater eutrophication, Human toxicity and Metal depletion. For the abovementioned impact categories, the dominant contributors are the production and the use of machines, ranging from 45% to 75%. Concerning Agricultural and Urban land occupation, the highest contribution is attributable to the shed, which shares approximately 50% of the total impacts. This hotspot reaches the maximum values in scenarios IV and V due to the larger surface occupied by the machines. However, its impacts on Land occupation are negligible from a quantitative point of view.

Figure 9: Incidence of environmental impacts per LCI category at the endpoint level (FU 1 h of olive harvesting).

In the scenarios in which nets were employed, this finding had a significant environmental impact, ranging from 15% to 25%. This trend is primarily due to the large amount of plastic that was used. In particular, scenario IV, in which a hand-held harvesting system was applied, showed the higher incidence of nets in environmental performance deterioration. However, it must be emphasized that the total environmental impact of this scenario has a value that is much lower than that of any other analyzed mechanical harvesting scenario.

Scenario VI displayed a different distribution of impacts, and, therefore, it must be analyzed separately. The fuel production and combustion represent the hotspots for Ozone depletion, Marine eutrophication, Photochemical oxidant formation and Natural land transformation, contributing at least 79%. For the Freshwater eutrophication, Human toxicity and Water depletion categories, the hotspot is represented by the nets, ranging from 65% to 90%. Climate change, Terrestrial acidification, Particulate matter formation, Ionizing radiation and Fossil fuel depletion are equally generated by fuel and nets. For the remaining categories, the impacts can be equally attributed to nets and hand-shaker production, which represent the biggest metal exploiter (87%).

Figure 10 shows the results reported in table 12 at the endpoint level. The passing of the level in terms of results expression leads to an increase in their uncertainty; however, the deviations between the examined scenarios are comparable with those present at the midpoint level. In this sense, the graphical presentation of the results at the endpoint level should be a quick way to show the performance of different “modules”.

Figure 10: Life Cycle Impact Assessment (LCIA) results at the endpoint level (FU 1 h of olive harvesting).

When a different FU is used other than 1 h of work, different conclusions can be drawn. In figure 11, the results are expressed per ha, and the yield differences described in paragraph 3.1 are considered in accordance with equation 1.

The opposite situation is shown in figure 12 in which, in accordance with equation 2, the results are influenced by the work capacity of the analyzed solutions, and the selected FU is 1 kg of harvested olives. In this case, the results are directly influenced by the yield per hectare of olive grove and by the physiological and technological characteristics of the drupes, especially those related to the size of the fruit, the length of the attached peduncles, the ripening degree and the peel strength. The most impactful categories for all the FUs were climate change and fossil fuel depletion, according to Pergola et al. (2013a), who attributed the role of one of the most impactful unitary operations in the olive orchard to the harvesting operation. The same result was obtained by Mohamad et al. (2014), who used inventory data comparable with the LCI results achieved in scenarios I, II and III. Considering the different LCIA methods and the more limited system boundaries for the harvesting operation, the results for the ha-FU can be compared with the aforementioned paper, in which the authors obtained an average single score for the harvesting operation in the productive stage equal to 15.5 pt. However, their system boundaries were limited to fuel and lubricant production and consumption, so it could be assumed that there was an equivalent value of 19.4 pt for scenario I, II and III.

Figure 11: Life Cycle Impact Assessment (LCIA) results at the endpoint level (FU 1 ha).

Figure 12: Life Cycle Impact Assessment (LCIA) results at the endpoint level (FU 1 kg of harvested olives).

These insights are closely related to the results of the technical trials and therefore cannot be generalized to define a performance ranking.

In comparing the endpoint results in terms of modules (1 h of olive harvesting), scenario V is once again the worst one, having an impact of approximately 16.5 times that of the best scenario (IV). By contrast, upon comparing the results per kg of harvested olives, scenario IV is the worst one because of its low work capacity, while the best scenario is I, which had three times better results. In this case, the results are comparable in terms of both functional units, which consider the work capacity and site characteristics. However, these results are not related to any performance index; therefore, the comparison is quite weak.

By contrast, the comparison between solution I and II deserves particular attention, given that only two scenarios have fully comparable characteristics. In particular, considering 1 ha and 1 kg of harvested olive as FUs, scenario I shows the best performance because the adopted harvesting solution, although characterized by the same productivity as that of scenario II, involves saving diesel and a lower tractor mass. Therefore, from the environmental point of view, solution I is better than solution II.

However, it is interesting to underline that the hand-held harvesting techniques (IV and VI) show poor environmental efficiency when considering one kg of harvested olives as the FU, just because of the poor work capacity of these harvesting techniques.

## ***3.4 Overall assessment***

The obtained results, considering 1 hour of harvesting operation as a FU, highlight that the scenarios where trunk shakers were employed (I, II and III) were more performant in terms of work capacity, however, they were more impactful from environmental point of view, due to the diesel combustion. This factor, jointly with the labor cost engenders high hourly costs (table 13). These results flip if one kg of harvested olives is considered as the FU for environmental and economic impact assessment, thanks to the high efficiency of environmental and economic resource employment. Scenario V has also high performances in term of work capacity but the high use of fossil fuels makes it the worst scenario for environmental impact. In addition, the rising of sensorial defects leads to discard this scenario. Hand held harvesting scenarios (IV and VI) are advantageous only in sites where mechanization is not possible and scenario VI results better than scenario IV thanks to the higher work capacity. Figure 13 summerizes graphically the obtained results (work capacity results are minimized in order to represent graphically the worst as the higher value). It shows a high heterogeneity of the analyzed scenarios. The scenario III may be considered a good compromise taking into account the different analyzed indicators thanks to its intermediate performances.

Table 13: Summary of the performance assessment (FU 1 h of harvesting)

Figure 13: Overall performance assessment (FU 1 h of harvesting)

## Conclusions

The further spread of modern, dynamic and mechanizable olive cultivation in Calabria is necessary for increasing their productivity and competitiveness. These innovations would hopefully enable a decrease in production costs, particularly those related to harvesting, which are currently very high. The rising requirement to modernize olive cultivation and the olive oil sector, which have assisted in the development of new growing models in recent years (Giametta & Bernardi, 2010; Tous et al., 2014), make it necessary to carefully plan the how to best use machinery to perform diverse agricultural practices, especially harvesting. The advantages in terms of working time and production cost abatement in this study are evident when employing self-propelled trunk shakers in an orchard predisposed to mechanical harvesting and accompanied by the adequate technical preparation of the driving operators.

The implementation of the modular LCA method allowed us to define a ready-to-use module for olive harvesting operations, and it is very easy to scale-up to different production contexts. However, to reach this goal, a broader dataset in different orchards with different yields and different conditions is necessary.

In addition, from an environmental point of view, the study highlighted that “Climate change” and “Fossil fuel depletion” are among the most impacted categories (Pergola et al., 2013b; Mohamad et al., 2014) in the olive production process. This finding confirms the significant role played by harvesting operations in the environmental sustainability of olive cultivation. The resulting study provides useful information to olive growers who want to deepen their knowledge about the olive harvest since it focuses on the technical, economic and environmental performances of different olive harvesting scenarios. Furthermore, LCA practitioners could use the findings of the modular assessment for studies on olive-growing, customizing the approch to their specific needs as performed in the present study using multiple scaling methods.

The determination of the most suitable harvesting system is complex and there is a need for a precise analysis of all the features that characterize the orchard. In light of the results, it is difficult to state a univocal outcome due to the heterogeneity of the studied harvesting sites, which represent a real reflection of olive cultivation in Calabria. Further studies considering ulterior scenarios, and taking into account different orchard conditions and harvest site organizations are need to confirm and improve the the outcomes obtained in this research.

**Acknowledgements:** The research was realized and funded in the framework of the National Operative Project PON Ricerca e Competitività 2007-2013, PON01_01545 OLIOPIÙ "Sistemi tecnologici avanzati e processi integrati nella filiera olivicola per la valorizzazione dei prodotti e dei sottoprodotti, lo sviluppo di nuovi settori e la creazione di sistemi produttivi ecocompatibili", funded by the Italian Ministry of Education, Universities and Research.

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Table 1: Average tree dimensional parameters at the analyzed harvesting sites (means ± SE)

| Harvesting sites | Planting layout (m) | Age (year) | Stem Ø (cm) | Stem height (m) | Canopy Ø (m) | Plant height (m) | Branch number |
|---|---|---|---|---|---|---|---|
| **I** | 6x4 | 25 | 26.35±0.69 | 1.31±0.19 | 4.58±0.23 | 5.65±0.14 | 3 |
| **II** | 6x4 | 25 | 26.80±0.83 | 0.98±0.41 | 5.96±0.89 | 4.27±0.76 | 3 |
| **III** | 6x4 | 25 | 22.05±0.57 | 0.90±0.51 | 4.26±0.51 | 4.64±0.10 | 3 |
| **IV** | 6x5 | 25 | 25.79±0.28 | 1.34±0.16 | 4.55±0.23 | 5.53±0.12 | 3 |
| **V** | 12x12 | 60 | 69.98±2.91 | 1.85±0.62 | 7.48±0.19 | 6.32±0.13 | 3 |
| **VI** | 8x6 | 60 | 43.95±0.91 | 0.80±0.8 | 6.49±0.31 | 4.74±0.41 | 3 |

Table 2: Olive trees and fruit characteristics at harvest (means ± SE)

| Harvesting sites | Canopy volume ($m^3$) | Fresh weight (FW) (g) | Fruit removal force (FRF) (N) | FRF/FW (N $g^{-1}$) | Olive yield (kg/tree) |
|---|---|---|---|---|---|
| **I** | 77.12±8.84 | 3.28±0.03 | 5.27±0.47 | 1.60±0.32 | 55.20±1.86 |
| **II** | 91.98±3.81 | 3.57±0.05 | 4.23±0.31 | 1.18±0.34 | 57.50±1.60 |
| **III** | 53.47±1.70 | 1.85±0.08 | 2.59±0.21 | 1.40±0.76 | 26.65±1.25 |
| **IV** | 70.95±7.73 | 2.46±0.04 | 4.44±0.15 | 1.80±0.06 | 15.98±0.56 |
| **V** | 202.12±15.5 | 2.01±0.08 | 2.81±0.17 | 1.33 ±0.06 | 61.90±0.87 |
| **VI** | 130.19±3.57 | 2.47±0.07 | 4.39±2.13 | 1.77±0.07 | 31.38±1.34 |

Table 3: Synthesis of the harvesting scenario composition

| Scenario | Employed machine/equipment | Labourer number | Slope |
|---|---|---|---|
| **I** | Self-propelled trunk shaker + nets | 6 | flat |
| **II** | Self-propelled trunk shaker + nets | 5 | flat |
| **III** | Towed radio-controlled shaker + nets | 2 | flat |
| **IV** | Olivspeed + mechanical pneumatic aids | 2 | flat |
| **V** | Trunk shaker + windrower + harvester from the ground | 3 | flat |
| **VI** | Small hand-held shaker + sticks + nets | 5 | >20% |

Table 4 - Calculation of the machine hourly cost (Miyata, 1980 modified)

| **COST ITEM** | **Symbol** | **Unit** | **Source** |
|---|---|---|---|
| Machinery value | MV | € | Price list |
| Equipment value | EV | € | Price list |
| Total value | TV | € | MV + EV |
| Salvage value | SV | € | % di TV |
| Power | P | kW | Technical manual |
| Interest rate | R | % | Market survey |
| Economic life | EL | years | Technical manual |
| Average annual machine use | AMU | h $year^{-1}$ | Field survey |
| Average daily machine use | DMU | h $day^{-1}$ | Field survey |
| Fuel price | FP | € $l^{-1}$ | Price list |
| Oil price | OP | € $kg^{-1}$ | Price list |
| Fuel consumption | FC | l $h^{-1}$ | Field survey |
| Oil consumption | OC | kg $h^{-1}$ | Field survey |
| Area occupied by the machine | A | $m^2$ | Technical manual |
| Price per $m^2$ | PA | € $m^2$ | Local market |
| Average hourly wage | HW | € $h^{-1}$ | Current local salary |
| Operator-machine | OM | N. | Field survey |
| ***Hourly Variable Costs*** | | | |
| Fuel consumption cost | FCC | € $h^{-1}$ | FC*FP |

| | | | |
|---|---|---|---|
| Oil consumption cost | OCC | € h$^{-1}$ | OC*OP |
| Operator-machine labour cost | OMC | € h$^{-1}$ | HW*OM |
| **Total hourly variable costs** | **HVC** | **€ h$^{-1}$** | **FCC+OCC+OMC** |
| ***Annual Fixed Costs*** | | | |
| Interest on capital goods | I | € year$^{-1}$ | ((MV+SV)/2) * r |
| Depreciation | DR | € year$^{-1}$ | (TV-SV)/EL |
| Insurance | IR | € year$^{-1}$ | Field survey |
| Maintenance | MR | € year$^{-1}$ | Field survey |
| Space cost | SC | € year$^{-1}$ | A * PA * (0.03) |
| **Total annual fixed costs** | **AFC** | **€ year$^{-1}$** | **I+DR+IR+MR+SC** |
| **Total hourly fixed costs** | **HFC** | **€ h$^{-1}$** | **AFC/AMU** |
| **TOTAL HOURLY COST** | **THC** | **€ h$^{-1}$** | **HFC + HVC** |

Table 5: Primary characteristics of the harvesting machines analyzed in this study

| **Scenario** | I | II | III | IV | | V | | | VI |
|---|---|---|---|---|---|---|---|---|---|
| Machinery | **Shaker harvester** | **Shaker harvester** | **Shaker machine with reversed umbrella** | **Pneumatic combs** | **Reversed umbrella** | **Shaker harvester** | **Windrower** | **Harvester from the ground** | **Hand-held shaker** |
| ***Purchase price (€)*** | 60,000.00 | 70,000.00 | 65,000.00 | 1,200.00 | 2,700.00 | 70.000,00 | 12,000.00 | 35,000.00 | 1,700.00 |
| ***Power (kW)*** | 72.5 | 105 | 58.0 | 1.45 | 1.44 | 105 | 13.05 | 43.5 | 1.45 |
| ***Economic life (years)*** | 15 | 15 | 15 | 5 | 10 | 15 | 10 | 15 | 5 |
| ***Average annual working time*** **(h year$^{-1}$)** | 480 | 480 | 480 | 300 | 300 | 480 | 300 | 300 | 300 |
| ***Fuel consumption*** | 8.2 | 9.08 | 5.05 | 0.58 | 0.29 | 8.2 | 1.3 | 4.5 | 0.71 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ***(l $h^{-1}$)*** | | | | | | | | | |
| ***Oil consumption (kg $h^{-1}$)*** | 0.05 | 0.05 | 0.05 | 0 | 0 | 0.05 | 0 | 0 | 0 |

Table 6 - Environmental Life Cycle Inventory - LCI (FU 1 h of olive harvesting)

| Scenario | Agricultural Machinery | Agricultural Equipment | Diesel | Shed | Lubricant | Net |
|---|---|---|---|---|---|---|
| | kg $h^{-1}$ | kg $h^{-1}$ | l $h^{-1}$ | $m^2$ $h^{-1}$ | kg $h^{-1}$ | $m^2$ $h^{-1}$ |
| I | 3.75E-01 | 5.00E-02 | 8.20E+00 | 9.17E-04 | 1.25E-03 | 8.18E+00 |
| II | 4.96E-01 | 5.00E-02 | 9.08E+00 | 1.00E-03 | 1.25E-03 | 7.55E+00 |
| III | 3.90E-01 | 5.00E-02 | 5.05E+00 | 1.25E-03 | 1.25E-03 | - |
| IV | 1.37E-02 | - | 8.70E-01 | 1.00E-03 | 2.50E-03 | - |
| V | 1.13E+00 | 2.35E-01 | 1.40E+01 | 2.38E-03 | 4.33E-03 | - |
| VI | 2.37E-03 | - | 0.71E+00 | 3.33E-04 | 1.67E-03 | 4.05E+00 |

Table 7 - Environmental Life Cycle Inventory - LCI (FU 1 ha)

| Scenario | Agricultural Machinery | Agricultural Equipment | Diesel | Shed | Lubricant | Net |
|---|---|---|---|---|---|---|
| | kg ha$^{-1}$ | kg ha$^{-1}$ | l ha$^{-1}$ | m$^2$ ha$^{-1}$ | kg ha$^{-1}$ | m$^2$ ha$^{-1}$ |
| I | 2.75 | 0.37 | 60.15 | 0.01 | 0.01 | 60.00 |
| II | 3.94 | 0.40 | 72.16 | 0.01 | 0.01 | 60.00 |
| III | 3.16 | 0.40 | 40.90 | 0.01 | 0.01 | - |
| IV | 0.53 | - | 33.39 | 0.04 | 0.10 | - |
| V | 2.40 | 0.50 | 29.78 | 0.01 | 0.01 | - |
| VI | 0.04 | - | 10.53 | 0.00 | 0.02 | 60.00 |

Table 8 - Environmental Life Cycle Inventory - LCI (FU 1 kg of harvested olives)

| Scenario | Agricultural Machinery | Agricultural Equipment | Diesel | Shed | Lubricant | Net |
|---|---|---|---|---|---|---|
| | kg kg$^{-1}$ | kg kg$^{-1}$ | l kg$^{-1}$ | m$^2$ kg$^{-1}$ | kg kg$^{-1}$ | m$^2$ kg$^{-1}$ |
| I | 1.38E-04 | 1.83E-05 | 3.00E-03 | 3.36E-07 | 4.58E-07 | 3.00E-03 |
| II | 1.97E-04 | 1.99E-05 | 3.62E-03 | 3.97E-07 | 4.97E-07 | 3.00E-03 |
| III | 3.16E-04 | 4.05E-05 | 4.09E-03 | 1.01E-06 | 1.01E-06 | - |
| IV | 1.59E-04 | - | 1.01E-02 | 1.16E-05 | 2.91E-05 | - |
| V | 6.00E-04 | 1.25E-04 | 7.44E-03 | 1.27E-06 | 2.30E-06 | - |
| VI | 6.75E-06 | - | 2.02E-03 | 9.51E-07 | 4.75E-06 | 1.15E-02 |

Table 9: Calculated work capacity and productivity

| Scenario | Work capacity | Work productivity | Harvesting efficiency |
|---|---|---|---|
| | [kg $h^{-1}$] | [kg $h^{-1}$ $worker^{-1}$] | % |
| I | 2,726.52$^{d}$ | 454.42$^{b}$ | 87 |
| II | 2,516.81$^{d}$ | 503.36$^{bc}$ | 84 |
| III | 1,234.60$^{b}$ | 617.30$^{c}$ | 90 |
| IV | 85.99$^{a}$ | 42.99$^{a}$ | 63 |
| V | 1,880.60$^{c}$ | 626.86$^{c}$ | 94 |
| VI | 350.69$^{a}$ | 70.13$^{a}$ | 81 |

Data followed by different letters are significantly different according to Duncan's test ($P < 0.05$)

Table 10: Chemical characteristics of the analyzed oils

| | I | II | III | IV | V | VI | Sig. | REG. UE 1830/2015 |
|---|---|---|---|---|---|---|---|---|
| **Acidity % acid oleic** | $0.12^a$ | $0.18^a$ | $0.24^b$ | $0.27^b$ | $0.36^c$ | $0.82^d$ | ** | ≤ 0.8 |
| **Peroxide value (meq $O_2$ $kg^{-1}$)** | $6.46^b$ | $5.00^c$ | $5.36^c$ | $9.45^a$ | $5.00^c$ | $4.45^d$ | ** | ≤20 |
| K232 | 1.71 | 1.62 | 1.90 | 1.80 | 1.80 | 1.50 | n.s. | ≤2.50 |
| K266 | 0.08 | 0.09 | 0.16 | 0.18 | 0.09 | 0.11 | n.s. | - |
| K270 | 0.11 | 0.09 | 0.14 | 0.14 | 0.14 | 0.11 | n.s. | ≤0.22 |
| K274 | 0.07 | 0.07 | 0.09 | 0.09 | 0.09 | 0.09 | n.s. | - |
| Delta K | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | n.s. | ≤0.01 |

Table 11: Results of the sensory analysis on orchard V olive oil

| **Analysis description** | **value** | **rVC %** | **Limits** |
|---|---|---|---|
| Defect median sensorial analysis | 1.9 | 11.3 | *md=0 |
| Fruity median sensorial analysis | 3.7 | 6.2 | *mf>0 |
| Bitter median sensorial analysis | 2.9 |  | * rVC % <20 |
| Hot median sensorial analysis | 4.1 |  |  |

Table 12: Life Cycle Impact Assessment (LCIA) results at the midpoint level (FU 1 h of olive harvesting)

| Impact Category | Unit | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|---|
| Climate change | kg CO2 eq | 3.36E+01 | 3.72E+01 | 2.36E+01 | 3.18E+00 | 5.32E+01 | 5.23E+00 |
| Ozone depletion | kg CFC-11 eq | 4.29E-06 | 4.86E-06 | 2.82E-06 | 4.54E-07 | 7.77E-06 | 3.99E-07 |
| Terrestrial acidification | kg SO2 eq | 2.81E-01 | 3.10E-01 | 1.91E-01 | 2.71E-02 | 4.38E-01 | 4.15E-02 |
| Freshwater eutrophication | kg P eq | 3.22E-03 | 3.61E-03 | 2.95E-03 | 1.79E-04 | 5.42E-03 | 7.25E-04 |
| Marine eutrophication | kg N eq | 1.58E-02 | 1.76E-02 | 1.03E-02 | 1.64E-03 | 2.67E-02 | 1.73E-03 |
| Human toxicity | kg 1,4-DB eq | 4.26E+00 | 4.79E+00 | 3.97E+00 | 2.41E-01 | 7.78E+00 | 7.95E-01 |
| Photochemical oxidant formation | kg NMVOC | 4.49E-01 | 5.04E-01 | 2.92E-01 | 4.68E-02 | 7.71E-01 | 4.72E-02 |
| Particulate matter formation | kg PM10 eq | 1.35E-01 | 1.51E-01 | 9.01E-02 | 1.36E-02 | 2.24E-01 | 1.68E-02 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 1.67E-03 | 1.68E-03 | 1.41E-03 | 6.18E-05 | 2.83E-03 | 1.28E-04 |
| Freshwater ecotoxicity | kg 1,4-DB eq | 9.25E-02 | 1.05E-01 | 8.47E-02 | 6.35E-03 | 1.72E-01 | 1.86E-02 |
| Marine ecotoxicity | kg 1,4-DB eq | 9.75E-02 | 1.12E-01 | 8.78E-02 | 6.96E-03 | 1.85E-01 | 1.81E-02 |
| Ionizing radiation | kBq U235 eq | 2.03E+00 | 2.35E+00 | 1.85E+00 | 1.28E-01 | 4.13E+00 | 3.35E-01 |
| Agricultural land occupation | m2a | 7.35E-01 | 7.88E-01 | 9.05E-01 | 5.70E-01 | 1.54E+00 | 2.71E-01 |
| Urban land occupation | m2a | 2.15E-01 | 2.33E-01 | 2.42E-01 | 1.40E-01 | 4.36E-01 | 6.75E-02 |
| Natural land transformation | m2 | 1.03E-02 | 1.17E-02 | 6.86E-03 | 1.10E-03 | 1.85E-02 | 1.03E-03 |
| Water depletion | m3 | 6.40E-02 | 7.20E-02 | 5.26E-02 | 7.13E-03 | 1.14E-01 | 1.17E-02 |
| Metal depletion | kg Fe eq | 1.42E+00 | 1.76E+00 | 1.42E+00 | 1.24E-01 | 4.05E+00 | 1.59E-01 |
| Fossil fuel depletion | kg oil eq | 1.10E+01 | 1.22E+01 | 7.75E+00 | 9.96E-01 | 1.77E+01 | 1.60E+00 |

Table 13: Summary of the performance assessment (FU 1 h of harvesting).

| Scenario | Work capacity | Environmental impact | Total Hourly Cost |
|---|---|---|---|
| | kg $h^{-1}$ | pt $h^{-1}$ | € $h^{-1}$ |
| I | 2,726.52 | 3.60 | 64.05 |
| II | 2,516.81 | 4.00 | 59.50 |
| III | 1,234.60 | 2.55 | 26.87 |
| IV | 85.99 | 0.36 | 20.43 |
| V | 1,880.60 | 5.89 | 72.05 |
| VI | 350.69 | 0.53 | 39.84 |

Figure 1: A self-propelled trunk shaker used in the harvesting o

Figure 2: The towed radio-controlled shaker used in scenario III

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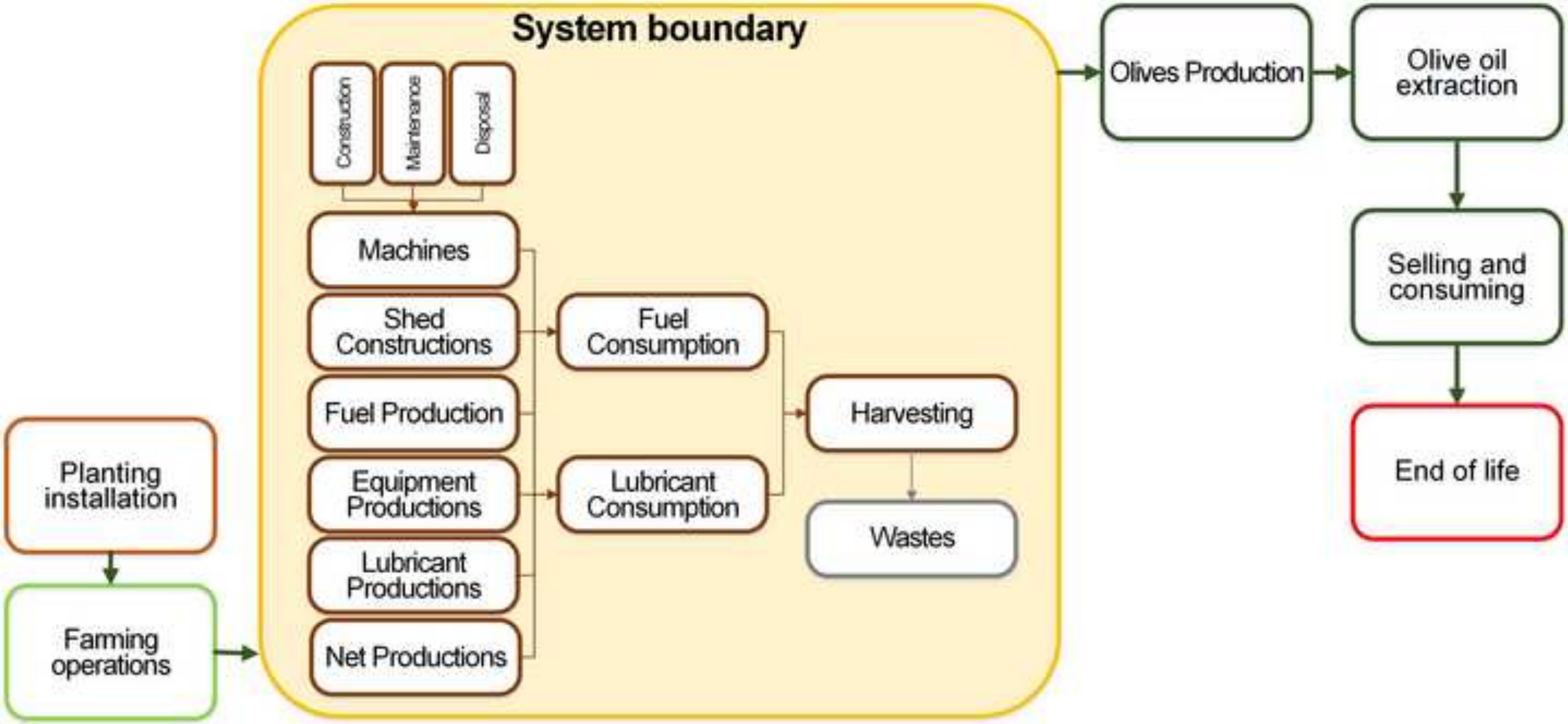
Figure 3: The Olivspeed used in scenario IV

Figure 4: Olive harvesting from the ground in scenario V

Figure 4: Olive harvesting from the ground in scenario V

Figure 5: Small hand-held shaker used in scenario VI

Figure 6: System boundary flow chart.



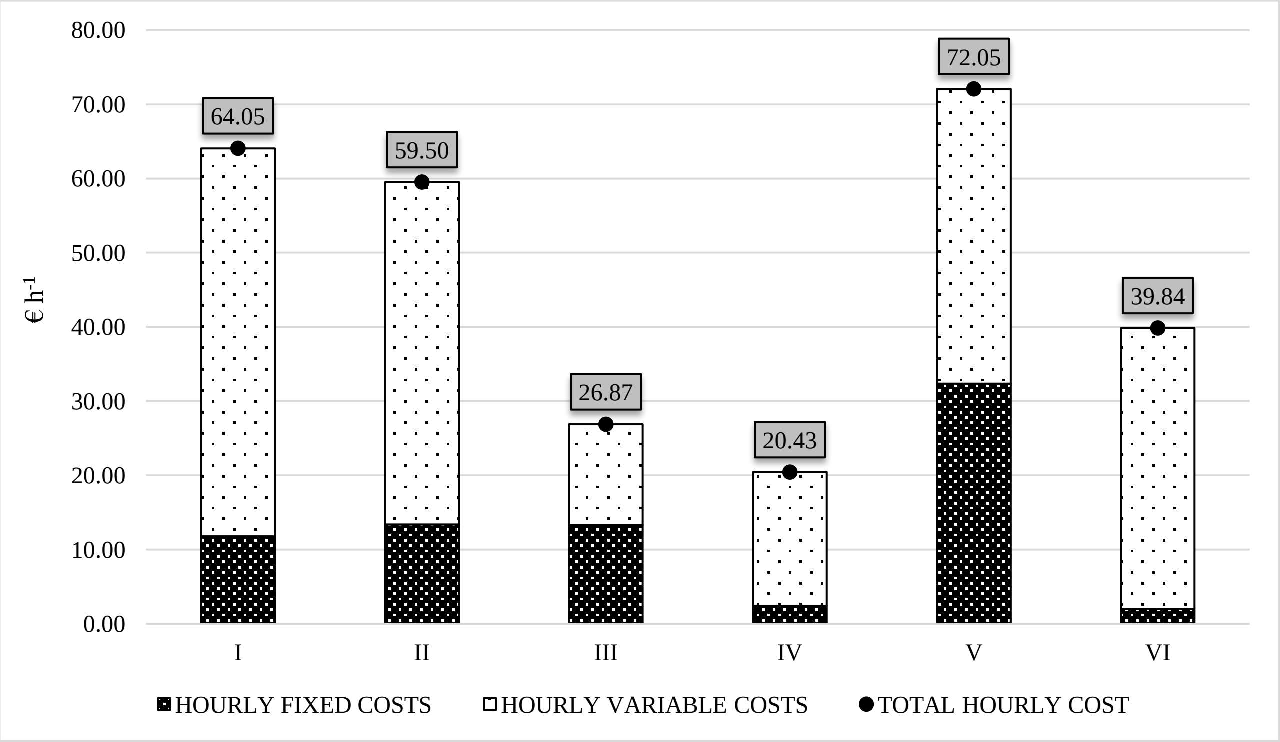


Figure 7: Harvesting hourly cost

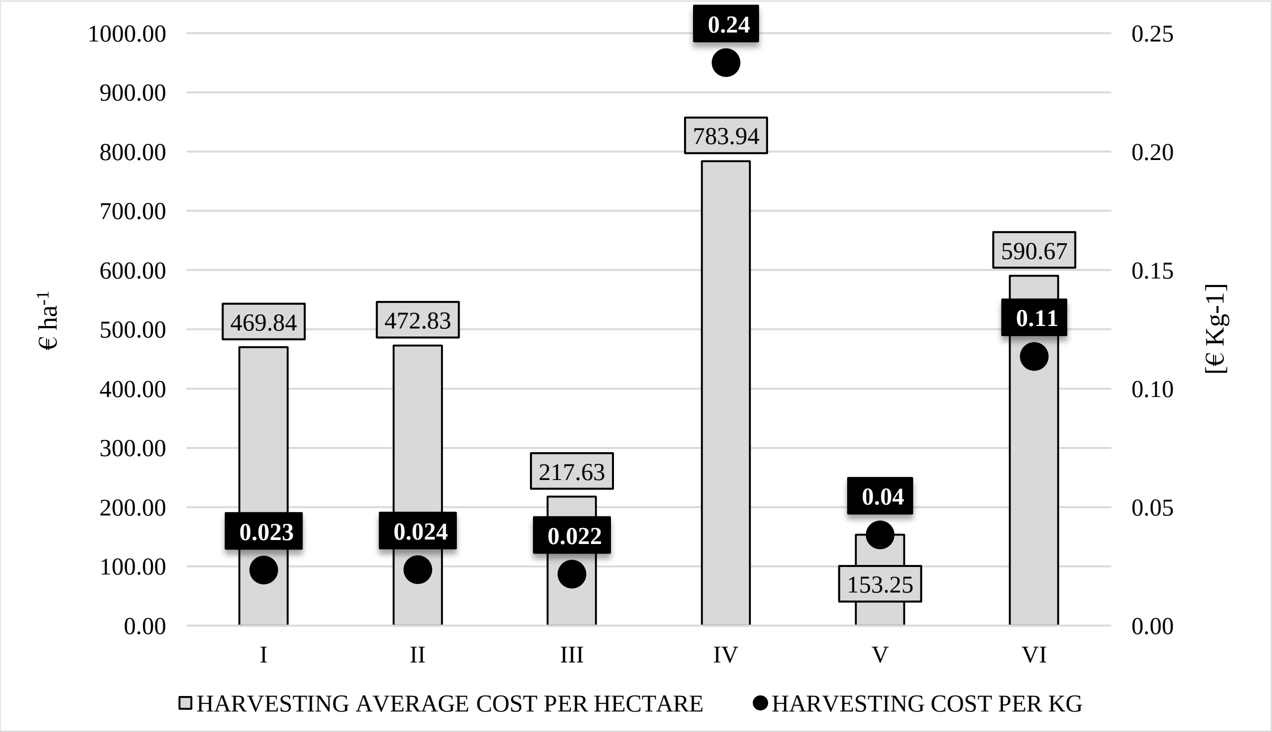


Figure 8: Unit cost per kg of harvested olives and the average cost per hectare

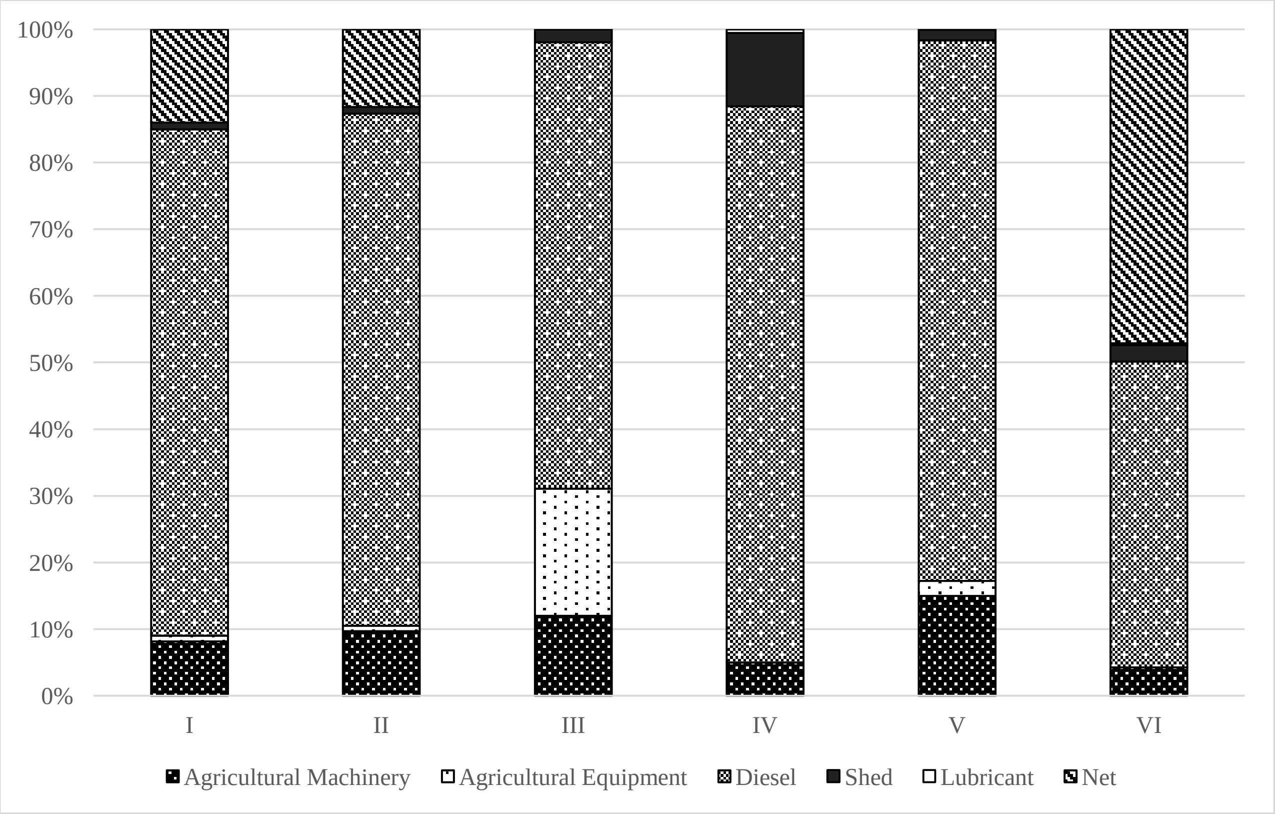


Figure 9: Incidence of environmental impacts per LCI category at the endpoint level (FU 1 h of olive harvesting)

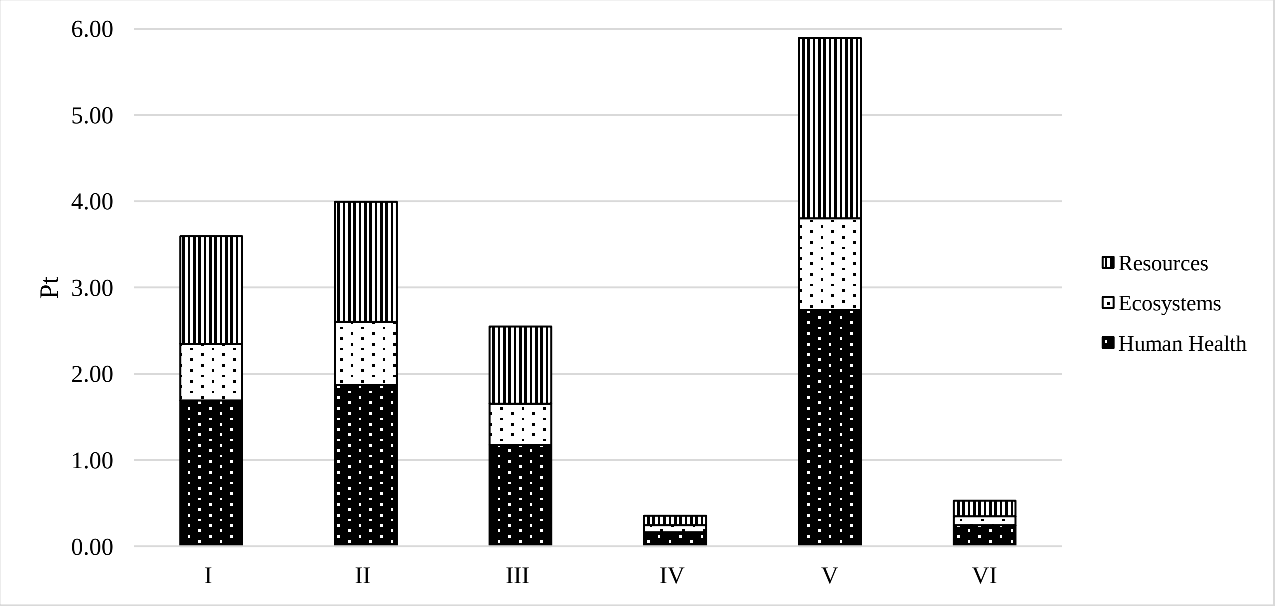


Figure 10: Life Cycle Impact Assessment (LCIA) results at the endpoint level (FU 1 h of olive harvesting)

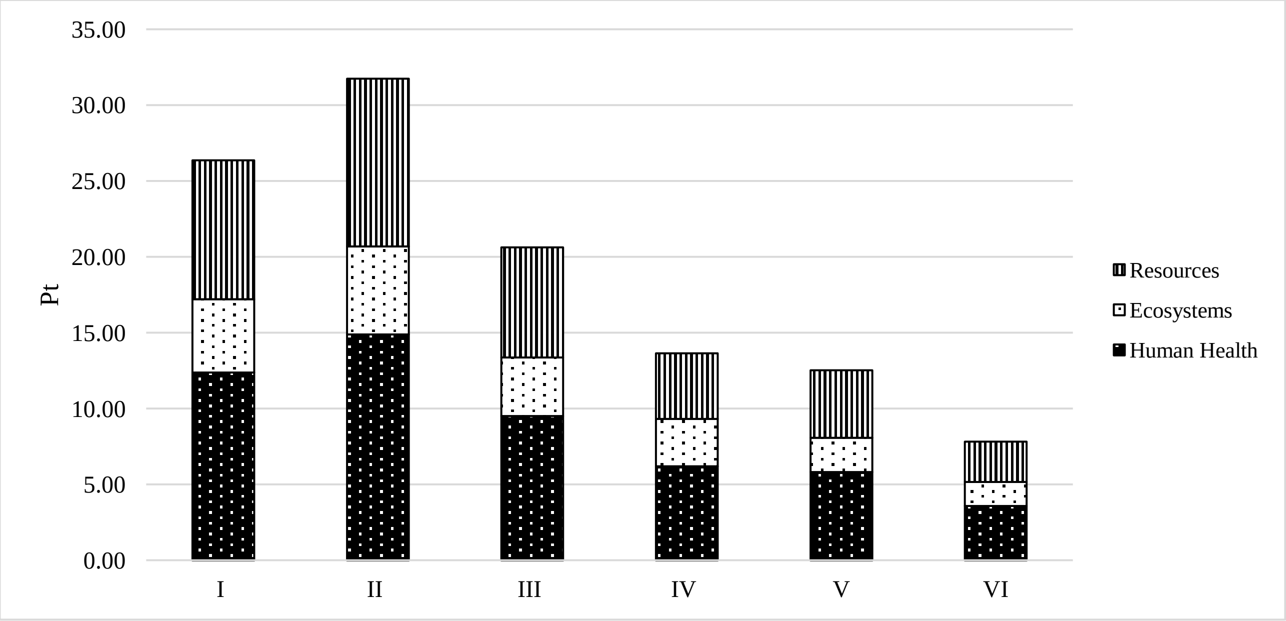


Figure 11: Life Cycle Impact Assessment (LCIA) results at the endpoint level (FU 1 ha)

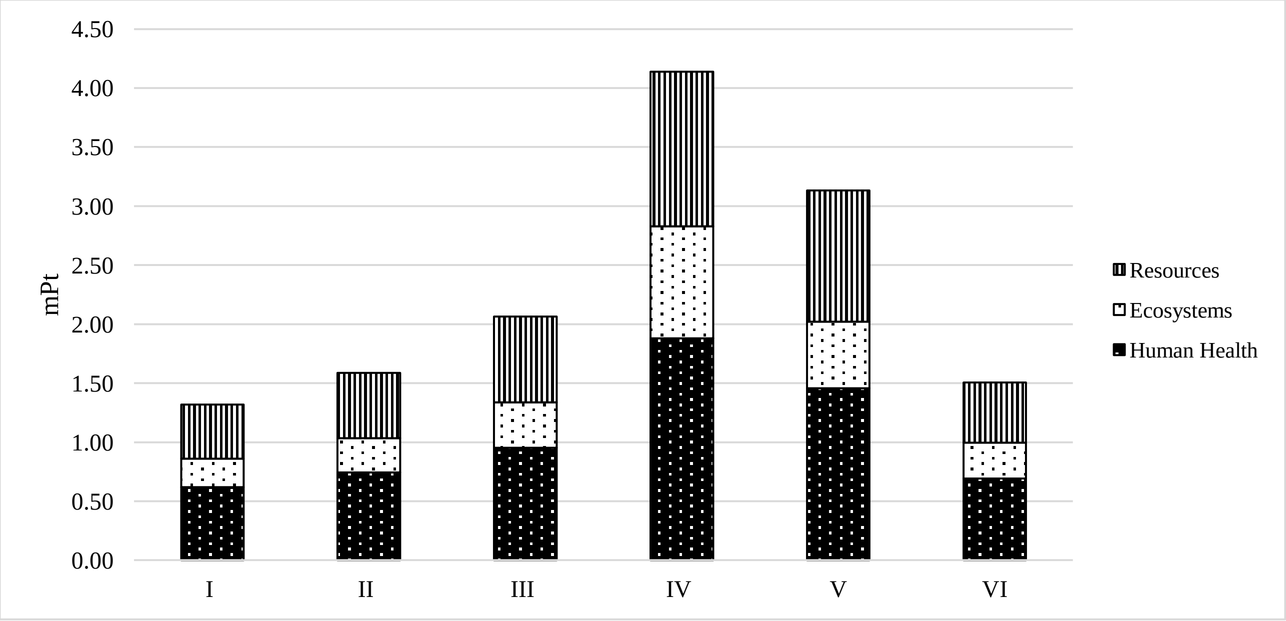


Figure 12: Life Cycle Impact Assessment (LCIA) results at the endpoint level (FU 1 kg of harvested olives)

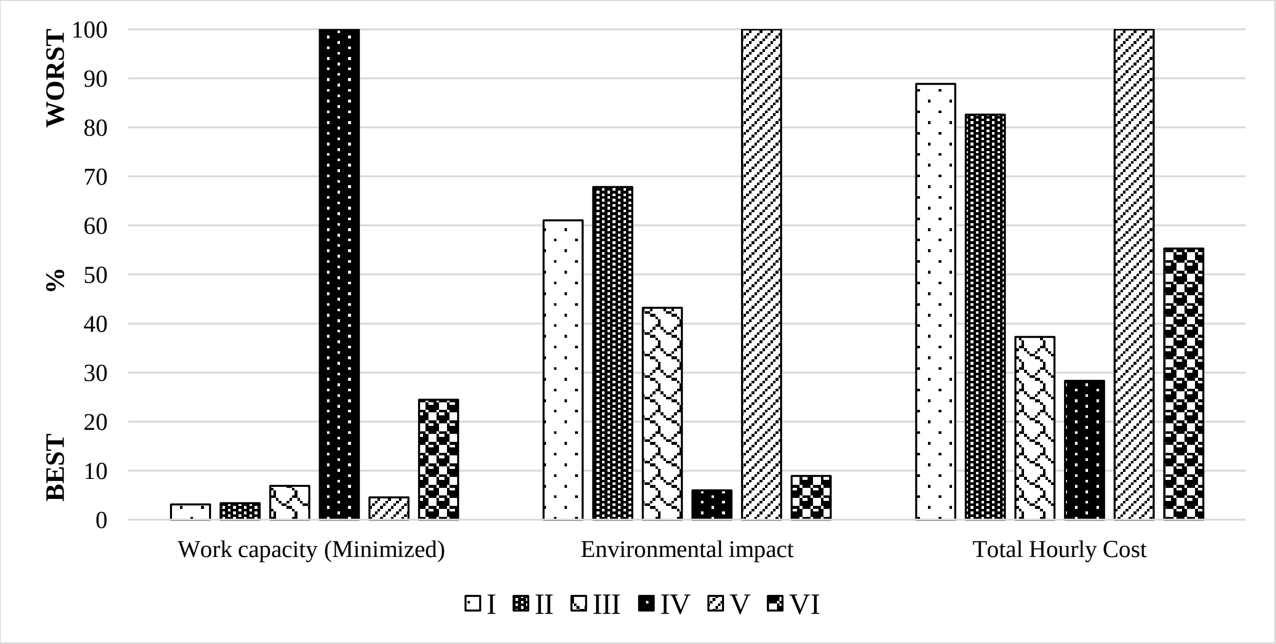


Figure 13: Overall performance assessment (FU 1 h of harvesting)