



Determining the key factors that contribute to the eco-efficiency level of honey production using life cycle approaches

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Abstract

Purpose Bees are essential to maintain the agriculture sector and provide not only pollination services, but also bee products. Honey is one of the most recognized products obtained from bees. In this sector, little attention has been paid to their environmental and economic performance, and their integration into the eco-efficiency concept. Consequently, this study analyzes the eco-efficiency level of honey production systems, identifying key resources to improve economic performance and reduce environmental impacts.

Methods Eco-efficiency is assessed by means of an indicator approach defined as the ratio between environmental and economic performance. The environmental one is measured by using the life cycle assessment (LCA), while the economic one is measured through profits, combining the life cycle cost (LCC) and income. The dataset corresponds to a sample of Chilean beekeepers considering a cradle-to-gate approach. The functional unit is 1 kg of honey produced. The productive factors covered are feeds, medicines, diesel, electricity, and disposable inputs. The LCA is carried out by using the software OpenLCA, and the ReCiPe midpoint method, while background data are obtained from the Ecoinvent v3.8 database. The economic data are analyzed using MS Excel[®].

Results and discussion Feeds are identified as the main contributor to the environmental and economic impacts, mainly due to sugar rations, i.e., a mix of sugar and water. In addition, most of the beekeepers used a higher amount of sugar for preparing these rations, compared with the quantity recommended in the literature. Diesel is another important source of environmental and economic impacts for beekeepers, mainly consumed for hive visits. Thus, reducing the frequency of visits or locating hives closer to beekeepers would improve their eco-efficiency performance. Concerning medicines, oxalic acid is the main contributor to environmental impacts, while amitraz is the main responsible in terms of costs, due to the higher dose applied compared with the literature. The environmental and economic impacts of electricity and disposable inputs are negligible.

Conclusions Feeds, medicines and diesel are the main contributors to the environmental and economic performance of the set of beekeepers analyzed, mainly due to the high amount consumed. Thus, focusing on these factors, beekeepers could improve their eco-efficiency performance by reducing both environmental impacts and cost, while increasing profit.

Keywords Eco-efficiency · Life Cycle Assessment · Profit · Life Cycle Cost · Honey · Beekeepers

1 Introduction

Agriculture is one of the most important sector of the economy, due to its key role in food production and natural resources conservation (Domagała 2021). As such, the environmental and economic performances of the agriculture sector have been a global challenge for many decades. The environmental performance, and the profit maximization are in the strategic core for organizations, so that

competitiveness and sustainability are objectives with the same importance (França et al. 2021). Thus, assessing these dimensions of sustainability can help identify key resources and develop policies (Caiado et al. 2017).

In the agriculture sector, bees are important not only for delivering pollination services, but also for providing products for human feeding. Human have maintained honeybee colonies and produced honey and other hive products worldwide for approximately 4500 years. The beekeeping sector plays an important role for smallholders generating additional revenues and better resilience for the rural

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inhabitants (Pocol et al. 2021). Some of the potential reasons that increase the attractiveness of beekeeping are that it requires little capital, it needs low maintenance and management costs, and it provides the opportunity to generate income in a relatively short time, among others (Altunel and Olmez 2019). However, according to Affognon et al. (2015), insufficient knowledge, environmental degradation and low production are some of the main challenges that this sector faces. Therefore, beekeepers need to weigh up the effects of direct costs of their activities (FAO 2021). In this context, a joint analysis of environmental and economic aspects of honey production systems can help to identify actions to improve both dimensions.

In order to monitor environmental and economic impacts of an organization, eco-efficiency has been developed by measuring economic activity, both in terms of consumption and production, as well as the corresponding impacts (Caiado et al. 2017). The World Business Council for Sustainable Development (WBCSD) defines eco-efficiency as “the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle, to a level at least in line with the earth's estimated carrying capacity” (Schmidheiny and Stigson 2000). Eco-efficiency assessment has been addressed using different frameworks, however, one of the most used is by means of ratios, combining the value of a product or service and their environmental impacts in a quantitative way. The use of ratios or indicators allows us to measure in a simple, systematic and consistent way two pillars of sustainability (Caiado et al. 2017), enabling a clearer and more comprehensive understanding of decision-making processes to improve economic performance and preserve natural resources.

The environmental dimension of eco-efficiency has been measured mainly through the Life Cycle Assessment (LCA), a widely used methodology that allows evaluating the potential impacts throughout the whole life cycle of products or services (Calado et al. 2019). This methodology could identify opportunities and improve the environmental performance of products or services (ISO 2006). The most recognized and measured LCA impact category is the global warming potential (GWP), also known as carbon footprint (CF). Although, employing solely one indicator to evaluate the environmental performance of products is easy to quantify with reasonable certainty (Calado et al. 2019), using only one evaluation indicator cannot represent the overall environmental impacts because some hints can be concealed. Furthermore, it is a well-known fact that when the ways to decrease impacts are based on one category, they may lead to an increase in another impact category of LCA (Hauschild 2015). Thus, the literature of eco-efficiency based on an LCA commonly employ different categories integrated into one environmental

indicator due to its simplicity for managers' interpretations (Caiado et al. 2017). However, in order to obtain these indicators, practitioners should carry out normalization and weighting steps of the LCA methodology. Nevertheless, these steps should be avoided in order to prevent further subjectivity in the analysis (Iriarte et al. 2012), and also some results can be hidden. Hence, reporting eco-efficiency levels by means of different environmental impact categories could provide more meaningful results.

The economic dimension of eco-efficiency has traditionally been analyzed employing the value of a product or service (Ilyas et al. 2021). This value can be expressed in terms of monetary, qualitative, or technical aspects, from which the monetary is commonly employed (Lorenzo-Toja et al. 2016). In this context, different monetary indicators have been applied, such as profit (Zhen et al. 2020), and costs (Oliveira et al. 2022). From these indicators, profit allows relating not only the cost of the organizations, but also their incomes, and consequently, the firm viability (Doole and Kingwell 2015). The use of profit as an economic indicator for eco-efficiency assessment in agriculture sector has not been widely addressed. Some studies that have recently utilized it are those of Zhen et al. (2020) for analyzing eco-efficiency of vegetable production, Liu et al. (2022), in composting processes for solid manure in intensive farms, and Saber et al. (2021) for analyzing different rice production systems. However, to the best of our knowledge, there are no previous studies analyzing profit and environmental life cycle assessment in honey production systems.

In honey production systems, environmental and economic dimensions have been addressed in a separate way. For instance, the environmental aspects have been analyzed in studies as those of Arzoumanidis et al. (2019), Kendall et al. (2013), Mujica et al. (2016), and Vásquez-Ibarra et al. (2021). While economic analyses have been carried out in studies as those of Goodrich (2019) and Goodrich and Goodhue (2020). However, based on our knowledge, there are not previous studies that combine both dimensions for eco-efficiency assessment. Only Rebolledo-Leiva et al. (2021) have evaluated the eco-efficiency of honey producers. However, in their research, the authors employed the LCA with a linear programming technique called Data Envelopment Assessment. Furthermore, CF is considered as the only environmental impact category.

Addressing the gaps mentioned earlier, the aim of this study is to analyze the eco-efficiency level of honey production systems, identifying key resources to improve economic performance and reducing environmental impacts. To this end, a case study of Chilean honey beekeepers is analyzed. This study is intended to offer a comprehensive environmental and economic analysis of a set of beekeepers, identifying hotspots and providing eco-efficient management practices.

2 Methodology

This section describes the case study and presents the environmental and economic methodology. Consequently, it is structured into four sections: (1) description of the case study, (2) environmental assessment using the LCA, (3) economic assessment; and (4) eco-efficiency assessment.

2.1 Chilean honey production

Chilean beekeepers produced 12,000 tons of honey in 2020, representing 1% of the honey produced worldwide (Iturra Molina 2021). In this country, 95% of the beekeepers are focused mainly on honey production, while the remaining 5% is divided into other bee products and pollination services. The central zone in Chile represents the main region for beekeeping activities. Particularly, the Maule region, located between the 35th and 36th parallel south, is the principal region for honey production, concentrating 18% of the national beekeepers and 19% of the national hives.

In this study, a sample of 22 Chilean beekeepers that produce honey from *Apis mellifera* bees in the Maule region is analyzed. The data was collected during the 2016–2017 season by means of a personal survey to the beekeepers, which is provided in Section SM1 in the Supplementary Material. This sample was previously analyzed in the works of Vásquez-Ibarra et al. (2021), where 31 beekeepers were evaluated from an environmental point of view using the LCA methodology. From these studies, 22 beekeepers provide operation data, costs, and incomes, which were analyzed in this study.

2.2 Environmental performance using the life cycle assessment

2.2.1 Goal and scope definition

The main goal of this study is to determine the eco-efficiency level of honey production of Chilean beekeepers. An additional goal is to identify the honey production

inputs that present the highest environmental and economic impacts, to serve as a source of information for improving the production level and benchmarking strategy in order to measure the progress in the beekeeping sector. The functional unit is defined as 1 kg of honey.

The scope used in this research is a cradle-to-farm gate analysis (i.e., until the production of raw honey without further processing after extraction), covering all stages from resources extraction, until the honey is ready for packaging. Thus, the productive factors covered are feeds, medicines, diesel for transport, electricity for extraction, and the consumption of disposable inputs used for the beekeepers' protection when they carry out hives maintenance and honey extraction. While the geographical boundaries correspond to the Maule region in Chile. Figure 1 presents the system boundaries of the honey production system analyzed (Vásquez-Ibarra et al. 2021).

2.2.2 Operational life cycle inventory

This step considers data collection and calculation procedures to quantify the relevant inputs and outputs of the operational life cycle inventory of a product system (ISO 2006). In this study, the inputs are the resources employed for honey production, while the output is honey produced. Table 1 presents the main statistical data description of the operational inputs and outputs. In addition, a detailed LCI is provided in Section SM2 in the Supplementary Material.

Regarding inputs, feeds are essential to offset the potential negative effects when bees cannot obtain natural feed (Kumar et al. 2013). Most of these feeds are based on sugar syrup prepared by beekeepers themselves, and supplements such as multivitamins, amino acids, among others. Medicines are provided to prevent or mitigate the potential impacts of diseases, mainly due to the varroa mite (*Varroa destructor*). Diesel is used for transport purposes of hives and beekeepers in all analyzed beekeeping systems. Transport of hives refers to the relocation of hives either to provide pollination services or to facilitate nectar collection. While transport associated with the beekeepers is mainly for hive visits, nectar collection or extraction. The average distance

Fig. 1 System boundaries of the honey production system, based on Vásquez-Ibarra et al. (2021)

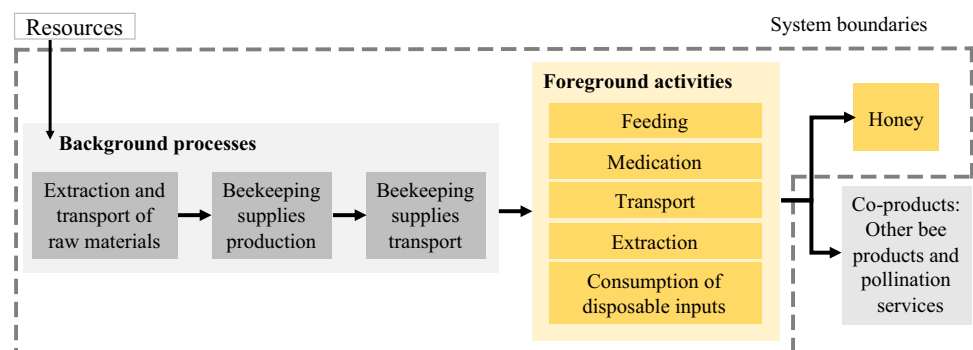


Table 1 Main statistical data of the life cycle inventory for producing 1 kg of honey

	Average	Maximum	Minimum	Standard deviation
Feeds (kg)	5.72E-1	1.68E+0	3.30E-2	4.17E-1
Medicines (kg)	5.39E-3	2.17E-2	2.20E-5	6.81E-3
Electricity (kWh)	4.71E-3	1.80E-2	6.60E-4	4.55E-3
Diesel (kg)	1.30E-1	6.18E-1	1.78E-2	1.61E-1
Disposable inputs (kg)	6.95E-4	2.01E-3	1.12E-4	5.19E-4
Honey produced (kg)	4,209.1	18,000.0	900.0	3,899.1

travelled, per kg of honey, was: 0.3 km for nectar collection, 1.2 km for visits, 0.2 km for honey extraction. Electricity is used for extraction and uncapping processes from the hives. Finally, disposable inputs refer to the items used by beekeepers for their protection during the hives related activities, such as gloves, suits, smokers, among others.

On the other hand, it is important to observe that some honey producers also obtain other co-products such as propolis (i.e., a natural resinous mix made by honey bees), pollination services, among others. Thus, in order to assign the environmental burdens to honey, an economic allocation method is used. The selection of this method is based mainly on the fact that honey cannot physically compared with pollination services. Particularly, allocation was addressed for the activities of feeding, medication, transport (visit and nectar collection), and consumption of disposable inputs. Further details can be found in the study of Vásquez-Ibarra et al. (2021).

2.2.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) method employed is the ReCiPe 2016 midpoint (H) to evaluate 18 environmental impacts categories. Table 2 presents the categories evaluated, their units, and acronyms for further identification throughout this article.

The impact assessment was carried out using the open-source software OpenLCA v.1.7.0 (Ciroth 2007), while the background processes were taken from the Ecoinvent® v.8.3 database (Wernet et al. 2016).

2.3 Economic assessment

As mentioned in the introduction section, profit is used as the economic indicator in this study, combining costs and income. Concerning costs, they are calculated using the life cycle cost (LCC). This methodology is commonly used to assess the costs along the whole life cycle of a given product, process or service (Pari et al. 2020). However, unlike the LCA, the LCC does not have a general standard to guide its implementation and use (França et al. 2021), which has complicated their usage as a decision-making tool (Simões et al. 2016). Even though, in most of the LCC studies, the

methodological choices selected for the LCA also applied for the LCC analysis.

The LCC goal and scope are consistent with those presented for the LCA analysis, as traditionally occurs in studies that combine LCA and LCC (Simões et al. 2016). Consequently, the FU presented for LCA analysis (1 kg of honey), and the system boundaries (cradle-to-farm gate) are also used for LCC analysis. The LCC was performed in three main modules: data collection, cost estimation and data interpretation. Data were obtained directly from the beekeepers during the season 2016–2017 by means of a personal survey to the beekeepers (see Section SM1 in the Supplementary Material).

The LCC is solely performed from the perspective of the production process, thus considering all direct cost of the beekeeping activities. In this way, the cost included are those of feeds, medicines, diesel, electricity, and disposable inputs. While labor, and depreciation of the active assets as centrifuge machine, automobile, etc., are not considered in the cost accounting because of the lack of data. Based on this,

Table 2 Environmental impacts categories evaluated

Category	Unit	Acronym
Fine particulate matter formation	kg PM2.5 eq	FPMF
Fossil resource scarcity	kg oil eq	FRS
Freshwater ecotoxicity	kg 1,4-DCB	FrEc
Freshwater eutrophication	kg P eq	FrEu
Global warming	kg CO ₂ eq	GWP
Human carcinogenic toxicity	kg 1,4-DCB	HCT
Human non-carcinogenic toxicity	kg 1,4-DCB	HnCT
Ionizing radiation	kBq Co-60 eq	IR
Land use	m ² a crop eq	LU
Marine ecotoxicity	kg 1,4-DCB	MaEc
Marine eutrophication	kg N eq	MaEu
Mineral resource scarcity	kg Cu eq	MRS
Ozone formation, Human health	kg NOx eq	OFHH
Ozone formation, Terrestrial ecosystems	kg NOx eq	OFTE
Stratospheric ozone depletion	kg CFC11 eq	SOD
Terrestrial acidification	kg SO ₂ eq	TeAc
Terrestrial ecotoxicity	kg 1,4-DCB	TeEc
Water consumption	m ³	WCon

the total cost for beekeeper i , $i = \{1, \dots, 22\}$, is determined using Eq. (1).

$$LCC_{honey_i} = Cost_{feeds_i} + Cost_{med_i} + Cost_{diesel_i} + Cost_{elec_i} + Cost_{disp_input_i} \quad (1)$$

where,

- LCC_{honey_i} : total cost of beekeeper i .
- $Cost_{feeds_i}$: total cost of feed used by beekeeper i .
- $Cost_{med_i}$: total cost of medicine used by beekeeper i .
- $Cost_{diesel_i}$: total cost of diesel used by beekeeper i .
- $Cost_{elec_i}$: total cost of electricity used by beekeeper i .
- $Cost_{disp_input_i}$: total cost of disposable input used by beekeeper i .

Once total costs have been determined, and considering the income from the sale of honey, the profit for beekeeper i is obtained using Eq. (2). All monetary data (cost, incomes, and profit) are expressed in US dollars (USD), and the average exchange rate between the Chilean currency (CLP) and USD in 2016–2017 are used, corresponding to 676.83 CLP per USD (Banco Central de Chile 2022)

$$Profit_i = income_i - LCC_i \quad (2)$$

2.4 Eco-efficiency assessment

In this study, profit has been used as an indicator of the monetary perspective to properly reflect the economic viability of a beekeeper, as used by Zhen et al. (2020). This indicator

is combined with the environmental impacts from the LCA to obtain an eco-efficiency indicator (EI). Since different categories are evaluated, this study presents one EI associated to each impact category. Following Zhen et al. (2020), the EIs are built as the ratio between profit of beekeeper i and the impact associated to the category j , as presented in Eq. (3).

$$EI_{ji} = \frac{Profit_i}{Environmental\ impact_{ji}} \quad (3)$$

where $Profit_i$ is obtained using Eq. (2), while $Environmental\ impact_{ji}$ refers to the result obtained for category j (see Table 2). According to Eq. (3), for increasing eco-efficiency level, the approach requires a reduction in the environmental impacts, an improvement in economic performance, or both.

3 Results and discussion

3.1 Environmental life cycle assessment

Figure 2 presents the relative contribution of the productive factors to the environmental categories analyzed. The detailed environmental results are provided in Section SM3 in the Supplementary Material.

As can be observed in Fig. 2, feeds represent the main source of emissions across most of the categories with an average of 73%, especially regarding WCon (97%) and

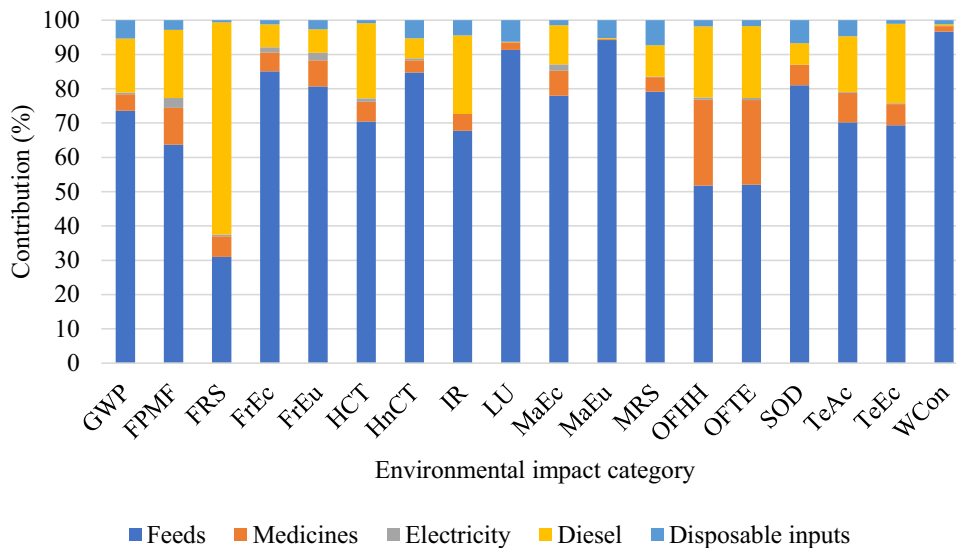


Fig. 2 Average contribution of the productive factors to the environmental impacts in honey production. FPMF: Fine particulate matter formation, FRS: Fossil resource scarcity, FrEc: Freshwater ecotoxicity, FrEu: Freshwater eutrophication, GWP: Global warming, HCT: Human carcinogenic toxicity, HnCT: Human non-carcinogenic toxicity, IR: Ionizing radiation, LU: Land use, MaEc: Marine ecotoxic-

ity, MaEu: Marine eutrophication, MRS: Mineral resource scarcity, OFHH: Ozone formation, Human health, OFTE: Ozone formation, Terrestrial ecosystems, SOD: Stratospheric ozone depletion, TeAc: Terrestrial acidification, TeEc: Terrestrial ecotoxicity, WCon: Water consumption

MaEu (94%). This is mainly attributed to the sugar used for sugar syrup. Vásquez-Ibarra et al. (2021) also identified feeds as the main contributors to environmental impacts. However, the authors do not delve into the main source (type of feed), as in this study. While in the FRS category, diesel is the main contributor, it represents the second main contributor in 10 categories (GWP, FPMF, FRS, FrEc, HCT, IR, MaEc, MRS, TeAc, and TeEc) with an average of 15%. Medicines have low impact across most of the categories, accounting for an average of 7%. This factor contributes mainly to the OFHH and OFTE categories due to the use of oxalic acid, the most frequent medicine used by beekeepers. In fact, this medicine is used by 12 beekeepers with an average of 4 g·kg of honey⁻¹. Finally, the impacts associated with electricity and disposable inputs are negligible because, on average, they contribute less than 5% in all categories.

3.2 Economic assessment

Table 3 presents the main statistical monetary data description of direct costs for each productive factor, the income, and the profit per FU. All values are expressed in USD. In addition, detailed values for each beekeeper are provided in Section SM4 in the Supplementary Material.

From Table 2, it is possible to observe that the total cost of honey production is, on average, 1.0 USD·kg of honey⁻¹, from which, feed was responsible for 41%, followed by diesel and medicine with 31% and 22%. Disposable inputs and electricity contribute 6% altogether. In addition, incomes are 3.1 times higher than the average costs, ranging from 1.1 (beekeeper 16) to 10.1 (beekeeper 4) on average. The average sell price of the sample analyzed is 3.1 USD·kg of honey⁻¹. It is important to highlight that the potential buyers of raw honey are either exporting companies (for international markets) or supermarkets (for national consumption), both being dominated by few companies with similar purchase prices (Cortés et al. 2015; Lerdon and Navarro 2018). This implies that the selling price of honey is similar (standard deviation of 0.57 USD·kg of honey⁻¹).

When focusing on the inputs with the highest costs (feeds, medicines, and diesel), some findings can be emphasized. Regarding feeds, pollen and sugar represent

the highest cost for beekeepers on average. Particularly sugar is a feed used by all beekeepers for sugar syrup preparations, with a ratio of three parts of sugar to one part of water. This amount is higher than the recommended by Somerville (2014) even for winter times where authors recommend two parts of sugar to one part of water. In addition, these authors stress that “a large amount of syrup fed all at once may have a reducing stimulus effect, compared to the slow release of the same amount of syrup over many days” (Somerville 2014). Thus, using the recommended amount of feeds could not only reduce the cost, but also induce a higher amount of honey produced. In the case of medicines, amitraz represents the highest cost per FU (0.2 USD·kg of honey⁻¹) widely. When the focus is on the amount of amitraz, it is possible to observe that beekeepers used on average 0.12 g of amitraz·kg of honey⁻¹. This is widely higher than the amount recommended by the European Agency for the Evaluation of Medicinal Products (1999) (2E-9 kg of amitraz·kg of honey⁻¹). Thus, its reduction would allow decreasing not only its cost, but also their impact on human health. Concerning diesel, its total average consumption is 130 g·kg of honey⁻¹, which results in 0.32 USD·kg of honey⁻¹, ranging from 0.001 USD·kg of honey⁻¹ (beekeeper 8) to 2.4 USD·kg of honey⁻¹ (beekeeper 16). Focusing on the three objectives of transport: nectar collection, visit and honey extraction, the average cost associated to each one is 0.034, 0.022 and 0.26 USD·kg of honey⁻¹, respectively. As can be observed, on average, the cost of visiting hives is almost five times higher than those associated to nectar collection and extraction altogether. Thus, in order to decrease the total costs associated with this factor, hives should be located closer to the beekeepers or, in turn, decrease the frequency of these trips. In addition, as mentioned in Sect. 2.3, this study analyzes small household beekeepers whose labor is mainly a family activity as is the case of the 80% of Chilean beekeepers (Castro 2017). In these cases, usually labor data are not registered and, consequently, we were unable to include this information. However, an estimation has been done considering that a beekeeper could manage 50 hives per day and that hives should be revised each 15 days (Lerdon and Navarro

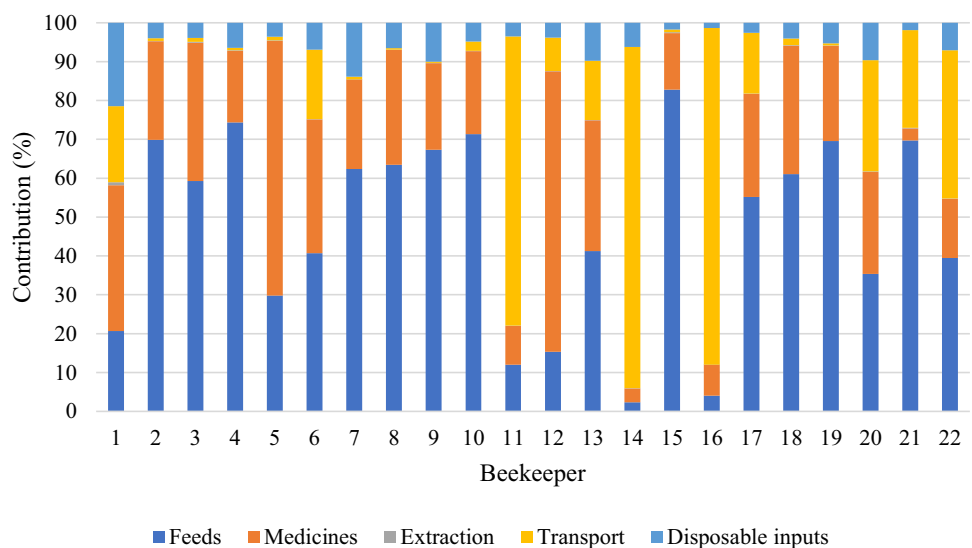
Table 3 Main statistical data of economic aspects for producing 1 kg of honey. All values are expressed in USD

	Average	Maximum	Minimum	Standard deviation
Costs of feeds	4.1E-1	1.2E+0	3.3E-2	3.2E-1
Costs of medicines	2.2E-1	5.5E-1	1.5E-2	1.5E-1
Costs of electricity	9.7E-4	3.0E-3	1.5E-4	7.6E-4
Costs of diesel	3.1E-1	2.4E+0	1.4E-3	6.4E-1
Costs of disposable inputs	5.5E-2	1.6E-1	7.4E-3	4.0E-2
Income	3.1E+0	4.4E+0	2.4E+0	5.7E-1
Profit	2.1E+0	3.6E+0	2.8E-1	7.5E-1

2018), and the minimum salary during 2016–2017 in Chile. Bearing in mind these assumptions, the inclusion of labor costs could imply in an increase of 1.1 USD·kg of honey⁻¹ on average. In this way, a cost estimation could be 2.1 USD·kg of honey⁻¹. Moreover, the maintenance of hives, which was not considered in the assessment, could represent about 1% of the investment according to Lerdon and Navarro (2018). However, future research is needed to address the estimation and inclusion of these costs in this type of farming systems.

Figure 3 presents the average contribution of each productive factor to the total cost for all beekeepers. Unlike the environmental performance, there is a higher variability in the percentage of contribution to the total cost among beekeepers. According to Fig. 3, feed is also identified as the main contributor for 14 beekeepers, followed by either medicines or transport depending on the beekeeper. Unlike these beekeepers, the total cost is highly dominated by medicines for beekeepers 5 and 12. These beekeepers spend, on average, 0.42 USD·kg of honey⁻¹ on medicines. The main cost of medicine for these both beekeepers is associated with amitraz, where they spend 0.50 USD·kg of honey⁻¹, representing, on average, 69% of the total cost. While for beekeepers 11, 14 and 16, the total cost is mainly dominated by cost of diesel, representing, on average, 83% of the total cost. Particularly, these three beekeepers spend on average 2.34 USD·kg of honey⁻¹, while the average cost associated to diesel in the sample is 0.32 USD·kg of honey⁻¹. The main reason behind this is the highest distance traveled by these three beekeepers mainly for hive visits, on average, 4.7 km·kg of honey⁻¹, while the average distance of visit trips in the sample reaches 1.2 km·kg of honey⁻¹. Thus, in order to decrease the total cost of beekeepers, they should pay attention to the amount of feeding, medicines and diesel used.

Fig. 3 Average contribution of each productive factor to the total cost in honey production



3.3 Eco-efficiency assessment

The eco-efficiency indicators are calculated using the results of the economic and environmental performance (see Sect. 2.4). Figure 4 presents the EIs for each category analysed of the honey systems under study. In addition, the detailed value of each EI is provided in Section SM5 in the Supplementary Material section.

As mentioned in Sect. 2.4, a beekeeper can obtain a higher EI due to either a lower environmental impact or to a higher profit. According to Fig. 4, the beekeepers that present the highest amount of EIs are beekeeper 12 (in 11 categories) and beekeeper 5 (in 10 categories). In the case of beekeeper 12, the highest values of EIs are because of their low environmental impacts based mainly on the low amount of feed per FU (0.15 kg·kg of honey⁻¹). On the contrary, in the case of beekeeper 5, the highest values of EIs are due to their higher profit. In fact, the income of this beekeeper is 6 times higher than their total cost. It is interesting to notice that beekeeper 4 generates even more income than their cost (10 times higher). However, this beekeeper also presents some of the highest environmental impacts and consequently, their EIs are found close to the average.

On the contrary, the beekeepers that present the lowest EIs are beekeeper 16 and 19. In both cases, the lowest EIs are associated to their low profit since their incomes are 1.1 and 1.6 times higher than their total cost. In addition, even though beekeeper 16 presents lower environmental impact in some categories, their lower profit implies a lower performance in terms of EIs. This unveils that the eco-inefficiency of these beekeepers is associated with a low economic performance.

When comparing the difference in terms of amount and type of productions factors that beekeepers used, with highest (5 and 12) and lowest (16 and 19) EIs, some findings

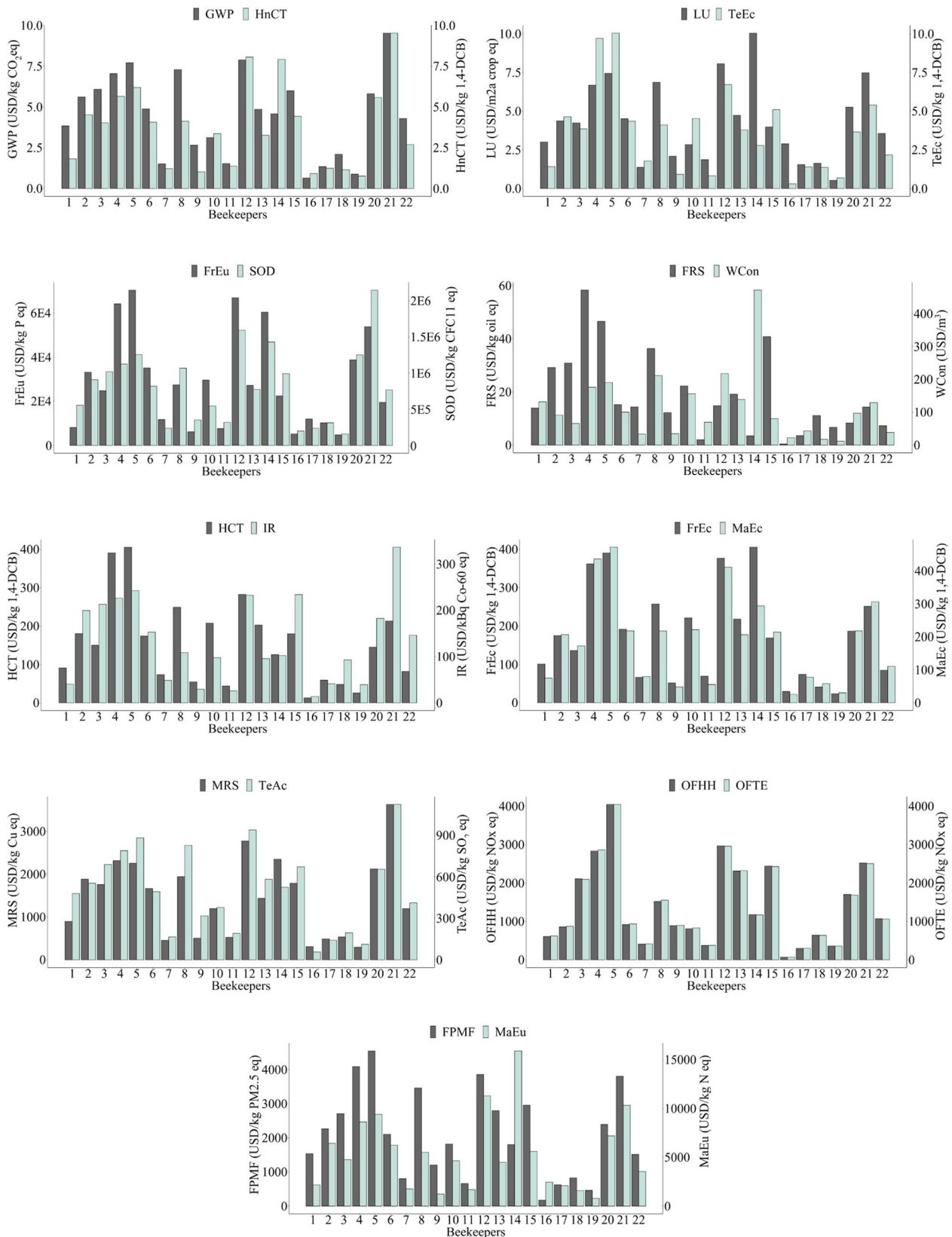


Fig. 4 Eco-efficiency indicators associated to the environmental categories analysed of honey production under study. For the environmental impacts' nomenclatures, see Table 2

can be highlighted. In terms of feeds, beekeepers 5 and 12 use a proportion of sugar of almost 1 to 1, while beekeepers 16 and 19 use a proportion of sugar to water of almost 3 to 1. As mentioned in previous section, a higher ratio of sugar to water could induce lower amount of honey and consequently, lower EI, as is observed in this case. In terms of medicines, there are no significant differences in the amount of oxalic acid (the greatest contributor to environmental impacts), since beekeepers 5 and 12 use, on average, 2.55 g·kg of honey⁻¹, while beekeepers 16 and 19 use 2.60 g·kg of honey⁻¹. However, in terms of amitraz (the greatest contributor to the total costs), there is a difference in the amount employed, since beekeepers 5 and 12 use, on average, 2 times lower the amount than beekeepers 16 and 19. In terms of diesel, in all cases visit trips concentrate the highest amount of diesel used. However, it is interesting to observe that beekeepers 5 and 12 use 3 times less diesel than beekeepers 16 and 19. This could be associated either to a higher frequency of the trips or a higher distance between beekeeper and hives. Finally, concerning electricity, diesel, and disposable inputs; there are no relevant differences with beekeepers 15 and 21.

The eco-efficiency performance of beekeepers can increase mainly when beekeepers used the recommended quantity of inputs. As observed previously, beekeepers that obtained lower EIs is because they use either a higher amount of resources or the type of inputs used present a high cost. Finally, this study unveils the relevance of providing managerial practices for beekeepers in order to improve their economic and environmental performance.

4 Conclusions

This research analyzed the eco-efficiency level of 22 Chilean honey production systems, identifying key resources to improve economic performance and reducing environmental impacts. To the best of our knowledge, this is the first study that uses LCA and profit for analyzing eco-efficiency of the beekeeping sector. In this way, this analysis allows the reduction of environmental impacts and increase the beekeeping monetary benefits.

Results show that feeds, diesel, and medicines are the main contributors to the eco-efficiency level. In the case of feeds, beekeepers used a higher proportion of sugar to water, compared with the recommended amount in the literature for preparing sugar rations. Regarding diesel, it is mostly consumed for hive visits. Thus, reducing the frequency of visits or locating hives closer to beekeepers would improve the eco-efficiency performance. Concerning medicines, oxalic acid is the main contributor to environmental impacts, while amitraz is the main responsible in terms of costs.

Furthermore, beekeepers use a higher amount of amitraz compared with the dose recommended by the literature.

Future research could include both variability and uncertainty assessments because of their relevance for costs and income analysis. In addition, climatic and geographical dimensions could be integrated into the analysis as a way to tackle the influence of these variables in honey production. Finally, it could be interesting to explore other allocation methods as the approach proposed by Arulnathan et al. (2022) to evaluate how the internal causality (i.e., the biological processes) could be applied to allocate the environmental burdens in honey production systems.

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Data availability All data analysed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interests The authors declare no competing interests.

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