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Economic and Environmental Assessment of Conventional Lemon Cultivation: The Case of Southeastern Spain

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Abstract: Spain is the world's leading producer and exporter of fresh lemons, with production concentrated in the southeast. The significance of this region in lemon production and the impact of agriculture on the economy and environment make optimizing lemon cultivation crucial. The main production models of lemon in Southeastern Spain (conventional Fino and Verna) are established and evaluated economically and environmentally through life cycle costing (LCC) and life cycle assessment (LCA). Both models have a similar cost structure, with variable costs (94% of the total) being the most significant, particularly labor and irrigation, followed by fertilizers and pest control. The key difference is in productivity; Verna has a higher unit cost due to lower productivity. As in LCC, in LCA the contributions of the components to the impacts of the models are very similar due to the similarities in the production models. However, Fino shows lower absolute values due to higher productivity. Fertilizers are the component with the highest contributions to the impacts, specifically their manufacture. For global warming, low values were obtained: 0.063 and 0.081 kg CO_2-eq·kg^{-1} for Fino and Verna, respectively, which may result from diverse factors: high productivity, low pesticide and machinery use, and low nitrous oxide emissions because of aridity. Additionally, a sensitivity analysis was performed on the origin of water sources and calculation methods of pesticide emissions.

Keywords: life cycle costing; life cycle assessment; lemon; conventional; environmental impacts; economic analysis

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1. Introduction

Agriculture plays a fundamental role in economic growth, accounting for 5% of the global GDP, and in less developed countries this figure can rise to more than 25% [1]. Agricultural activity, in addition to providing economic development and creating jobs through the generation of raw materials and food, is an essential tool for achieving global challenges such as eradicating hunger and feeding a growing population that is estimated to reach 9.7 billion in 2050 [2]. However, in line with the twelfth Sustainable Development Goal "responsible production and consumption", to guarantee food security it is essential to separate economic growth from environmental degradation, increasing efficiency in the use of resources and promoting sustainable lifestyles [3].

Among the different economic sectors, the agri-food sector contributes significantly to environmental impacts due to its intensive production model highly dependent on machinery, fertilizers, pesticides, energy, etc. [4–6]. In the European Union (EU), it is responsible for 10% of the greenhouse gas emissions [7], represents 40% of the water demand [5], and is the main cause of species and habitat loss [8]. Given this situation, agriculture is one of the priority focuses of European policies to stop environmental degradation.

The Green Deal encompasses the Farm to Fork and Biodiversity strategies that affect the EU food system and try to make it more sustainable [9]. Among their environmental commitments are reducing the use of phytosanitary products and fertilizers, increasing the area of organic agriculture and protected spaces, reducing food waste, and reversing the trend in declining pollinators [7,8,10]. From Farm to Fork also focuses on social and economic aspects. It aims to facilitate access to nutritious, affordable, environmentally friendly foods in sufficient quantity and to improve the transparency of products through labeling. Likewise, it promotes fair trade that guarantees, among other things, a decent income for producers. The CAP Strategic Plan for 2023–2027 is adapted to the Green Deal and offers a series of measures to member states that will be one of the essential tools in achieving these objectives.

Among the main agri-food products produced by the EU is the lemon [11]. Spain is the EU leader in this product, representing approximately 60% of the European production and crop area in 2022. According to the data provided by the Interprofessional Lemon and Grapefruit Association of Spain (AILIMPO), on a global scale in the period 2013–2022, Spain contributed 18% of the total lemon production, ranking it second, only behind Argentina. However, it was top in fresh production with 837,512 tonnes per year, followed by Turkey (803,500 t), the USA (635,100 t), and Italy (418,600 t). In this same period, Spain occupied first place in the ranking of fresh exports, exporting more than half of its production, with the principal destinations being European countries.

The lemon tree is not very tolerant of low temperatures and high humidity, so in mainland Spain its cultivation is very localized, essentially taking place in semi-arid areas of the southeast (SE) of Spain. Alicante, Murcia, and Almería are the areas in the SE of Spain that concentrate around 80% of the national production. The Region of Murcia (SE of Spain) is the main producer; the area dedicated to lemon crops here has followed an upward trend in the last 10 years, covering 26,987 hectares in 2022 (52% of the national area). In the period 2013–2022, production in Murcia represented around 53% of the Spanish total. These data show the good adaptation of the crop to this territory and the high technological level and intensification involved [12]. The main varieties grown are Fino and Verna, as they allow lemons to be harvested throughout the year, but their differences also cause seasonality in production and prices. The main destination for lemons is the fresh market. These two factors are also reflected at a national level.

Given the importance of the lemon sector as manifested by statistical data and the impact that agriculture has on the economy and the environment, it would be of interest to optimize lemon cultivation. To do this, reliable economic and environmental evaluation methods are needed that allow the identification of critical points for which action can be taken and strategies formulated that make them more efficient from the perspective of sustainability [13].

Life cycle assessment (LCA) is a standardized methodology used to quantitatively evaluate the environmental impacts generated by a product, process, or service throughout its life cycle [14,15]. LCA is consolidated internationally and supports numerous policies [6,16,17]. Life cycle costing (LCC) is the methodology that accounts for all the costs of the life cycle of a product, process, or service and is recognized as the most used economic analysis methodology along with LCA [6]. LCC analysis arose before LCA and the term "sustainable development" and has been used since the 1960s [17,18]. Although there is growing interest in its application and various procedures have been developed to harmonize it, a generic calculation method applicable to any system has not yet been reached [6,18,19], but there are different standards [20,21] and bibliography [18] that can serve as references to carry it out.

Both LCC and LCA have already been applied in the economic and environmental evaluation of agri-food products [6,22–24], including the general case of citrus fruits and specifically for lemon [25–27]. As indicated previously [24,28,29], their combination is proving to be useful in the evaluation of the sustainability of agricultural production systems, since the quantification of the production and environmental costs of a system allows economically profitable scenarios with the lowest possible environmental impact to be achieved.

In an extensive literature review on the application of LCA in the citrus sector, Cabot et al. [30] pointed out that in the cultivation phase, fertilizers (production and soil emissions due to nitrogen fertilization), irrigation, and fuel consumed by machinery are usually identified as the factors with the greatest environmental burdens. The LCC of citrus fruits does not follow the same evaluation method and does not usually contemplate the same accounting items, with the results differing substantially from one work to another, which could be due to the lack of a standardized methodology. In any case, the works of Pergola et al. [26] and García García [31] highlight that in the accounting structure, the greatest weight is for variable costs and among these, the items linked to labor, irrigation, and fertilizers. Sgroi et al. [32] also pointed out that the highest costs in conventional lemon production are linked to labor and material inputs such as fertilizers.

The results of this type of study present variability derived from the sensitivity of agriculture to climatic and edaphic factors, cultivation practices, and plant material [24,27,30,33]. In addition to this, uncertainty arises from the data used and the differences in the methodology applied [30,34]. In this sense, the SE of Spain in general is a representative area of lemon cultivation and is subject to a series of conditioning factors that make it noteworthy. It is a semi-arid area subject to desertification due to the scarcity of water resources [24,35–37]. The soils have limiting characteristics from an agricultural perspective: high pH, high active limestone content, and low organic matter, among others [24]. Also, the production of fresh lemons—in the context of intensive, professional, irrigated agriculture, characteristic of SE of Spain—is highly technical and is based on varieties closely linked to the territory. All these factors make it a differentiated and specialized system, which, in view of the above, requires its own study.

Thus, the objectives of this work are as follows:

1. The establishment of the two lemon cultivation models representative of the SE of Spain, which correspond to the two principal varieties (Fino and Verna) and the main (conventional) production system.
2. To apply life cycle costing and life cycle assessment to the two production models to evaluate and compare them economically and environmentally.
3. To carry out a sensitivity analysis, granting variability to the elements identified as relevant in previous evaluations and proposing more efficient alternatives.

This study is supported by the citrus sector through AILIMPO, which, aware of the current situation, requires scientific evidence to make key decisions focused on better management of its productive systems from the sustainability perspective.

2. Materials and Methods

2.1. Data Collection

The data on the production process for the establishment of production models were obtained within the framework of a contract signed by the Bioeconomy team of the Murcian Institute of Agricultural and Environmental Development (IMIDA) and AILIMPO.

AILIMPO represents 95% of the Spanish lemon production, exceeding the 75% minimum representativeness required by Law 38/1994 for agri-food interprofessional organizations. This has allowed AILIMPO to carry out an extension of the regulation for the entire sector (Order APA/541/2020).

The information used came from conducting on-site surveys of technicians from AILIMPO, as well as technicians who work in the Regional Agricultural Offices (OCAS) and in leading companies in the regional sector associated with AILIMPO.

Based on this information, a production model was established for each of the main lemon production systems in the southeast: conventional Fino and conventional Verna. These models encompass the representative practices of lemon cultivation in the SE of Spain.

2.2. Characterization of the Study Area

Spanish lemon production is mainly concentrated in three areas located in the SE: Almería, Murcia, and Alicante (Figure 1). Within these areas, the Region of Murcia stands out as the main producer.

Figure 1. Localization map of lemon production in the SE of Spain: the study area.

These areas have limiting edaphoclimatic conditions from an agronomic perspective.

They have a semi-arid climate, with dry and hot summers and mild winters, in which rainfall is scarce and irregular, and in many cases can be torrential [13,24,38]. The average annual precipitation in the last 10 years in these areas is 308 mm while the potential evapotranspiration is 1304 mm, which translates into a water deficit.

The soils have a clayey loam or clayey sandy loam texture, with a low amount of organic matter, high pH, and high content of calcium carbonate and active limestone [24].

2.3. Establishment of Production Models

In order for the evaluation to accurately reflect the reality of the sector, the following models were established:

- Fino conventional

The Fino lemon tree is the most widespread in the SE of Spain and is characterized by being tough, productive, and vigorous [39]. It enters production earlier than Verna and is more stable from a productive perspective, although the useful life of the plantation is shorter and the quality of its fruits is lower. The flowering is more concentrated, with blooming in spring (March–April). These fruits are harvested from October to January, they have thin skin, and their conservation on the tree is shorter than in Verna. The first fruits reach a higher value due to the lack of production at this time in competing countries in the international market [40]. Within Fino, the varieties "Fino 49" and "Fino 95" stand out. The former is more widespread; it is more productive and more resilient, and its fruits have a longer useful life. However, "Fino 95" has the commercial advantage of an earlier harvest, by up to 15 days, in those areas that climatologically allow such precocity. The Fino lemon tree is widely grafted on the *Citrus macrophylla* Wester rootstock, and to a lesser extent, on the bitter orange *Citrus aurantium* L. [31,39–43].

A professional cultivation model was established with an area of 10 hectares and a plantation spacing of 7 m × 5 m, which is equivalent to about 286 trees·ha^{-1} (Table 1). It was estimated that the useful life of the Fino lemon tree is 25 years, taking 5 years to reach full production: the first year is unproductive and from the second to the fifth year, production increases in relation to some coefficients (Table 2). For the remaining 20 years, adult trees have an average annual gross production of 46,000 kg·ha^{-1} (with around 20% of the fruits being non-fresh marketable). The water resources applied are 5800 m^3·ha^{-1}. The characteristics established for the models are within the range of values presented in the literature for lemon trees in the SE of Spain [31,43,44].

Table 1. Agronomic data of the two cultivation models of lemon production.

	Fino Conventional	Verna Conventional
CHARACTERISTICS		
Useful life (years)	25	30
Plant spacing (m × m)	7 × 5	7 × 5
Yield in productive years (kg·ha^{-1})	46,000	31,000
Non-fresh marketable yield (industry) (%)	20	17
Non-productive years	1	1
Partially productive years	4	5
INPUTS IN PRODUCTIVE YEARS		
Machinery hours (h·ha^{-1})	14.25	13.75
Diesel consumed by machinery (l·ha^{-1})	136.96	131.06
Fertilizers (N-P_2O_5-K_2O-CaO-MgO)	(190-70-140-20-10)	(160-60-120-15-8)
Phosphoric acid (l·ha^{-1})	84.10	72.10
Ammonium nitrate (kg·ha^{-1})	98.60	85.70
Urea ammonium nitrate (l·ha^{-1})	258.00	216.90
Potassium nitrate (kg·ha^{-1})	304.30	260.90
Calcium nitrate (kg·ha^{-1})	74.00	55.70
Magnesium nitrate (kg·ha^{-1})	62.60	50.00
Fe chelates (kg·ha^{-1})	17.15	14.30
Humic and fulvic acids (l·ha^{-1})	42.90	35.70
Zn and Mn chelates (l·ha^{-1})	6	6
Amino acids (l·ha^{-1})	4	4
Phytosanitary treatments		
Bacillus thuringiensis (kg·ha^{-1})	1.50	1.50
Neoseiulus californicus (n° insects·ha^{-1})	1000	1000
Sexual confusion traps (units·ha^{-1})	-	30
Paraffin oil (83%) (l·ha^{-1})	60.00	60.00
Spirotetramat (10%) (l·ha^{-1})	1.80	1.80
Piriproxifen (10%) (l·ha^{-1})	1.50	1.50
Hexitiazox (10%) (l·ha^{-1})	0.60	0.60
Glyphosate (l·ha^{-1})	8.00	8.00
Irrigation		
Water (m^3·ha^{-1})	5800	5200
Fertirrigation electricity (kWh·ha^{-1})	714.70	640.13

Table 2. Coefficients applied to the production of Fino and Verna for the development years.

Gross Production	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Coefficients for Fino conventional (%)	0	8	25	50	80	Adult
Coefficients for Verna conventional (%)	0	8	20	40	60	80

- Verna conventional

The Verna lemon tree has the disadvantages of being less vigorous and productive than the Fino, having a later entry into production and irregular harvests ("vecero": a year with a high yield being followed by a year with little or no yield). On the other hand, it produces higher quality fruits and the useful life of its plantations is longer. It has greater reflowering than Fino, but its main flowering occurs from March to May. The fruits are harvested starting in February of the following year, and the harvest can last until July, although the last fruits have a lower commercial value. The second flowering occurs in August–September and the harvesting of these fruits ("rodrejos") usually occurs in August–September of the following year [40]. Within Verna, the most planted varieties in Murcia are "Verna 62" and "Verna 51". Most of the Verna lemon trees are grafted on the *Citrus macrophylla* Wester rootstock. Grafting on *Citrus aurantium* L. is also common, but to a lesser extent, using intermediate wood of sweet orange (*Citrus sinensis* L.). The intermediate wood avoids the "crinoline", a protuberance in the graft area caused by the physiological incompatibility between the lemon tree and the bitter orange tree, very noticeable in Verna [31,39–43].

A productive model was established with an area of 10 hectares and a spacing of 7 × 5 m (approximately 286 trees$\cdot$ha^{-1}) (Table 1). The useful life of the Verna lemon tree is 30 years, with 6 years of development: the first year is unproductive and from the second to the sixth year, the production evolves according to the coefficients set out in Table 2. The rest of the years (24) are considered fully productive. The average gross productivity is 31,000 kg$\cdot$ha^{-1} (17% of the production is non-fresh marketable) and the water resources used are 5200 m$^3\cdot$ha^{-1} [31,39–43].

2.4. Economic Evaluation: Life Cycle Cost Analysis

For the economic evaluation of the models, LCC was used, which accounts for all the costs of the life cycle of a product, process, or service. In this case, LCC was used to economically evaluate two lemon cultivation models: conventional Fino and conventional Verna. To be complementary to the LCA, the same system boundary was used: the cultivation phase. The results are expressed in euros (EUR) per the functional unit used in the LCA (FU: 1 kg of lemons). However, the cost structure will also be presented in euros (EUR) per unit area (hectare), since this is the most common in the economic analyses of an agricultural nature [26,31,32]. The prices used to calculate the costs were extracted from the Price Database of the IMIDA Bioeconomy Team, which is based on information provided by companies in the sector through surveys.

The cost analysis was carried out by accounting for all the phases of conventional Fino and Verna lemon cultivation: preparation and planting, tree development, and the adult stage. It is important to highlight that the main cost structure presented is that of a year in full production. Notwithstanding, the compensated costs per kilogram will also be presented taking into account the development phase. For the development years, inputs, as well as production, were calculated by applying a coefficient to the production cycle of adult trees (Table 3).

Table 3. Coefficients applied to the variable costs of Fino and Verna for the tree development years.

Variable Costs	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Coefficients for Fino conventional (%)	20	35	60	75	85	Adult
Coefficients for Verna conventional (%)	20	30	45	65	80	90

The costs were subdivided into fixed costs and variable costs [22,26,31,32,45,46] and for each of them, the opportunity cost was taken into account [47], that is, the alternative use of money in risk-free savings bank accounts. The opportunity cost in this case was 1.5%. The land was considered to be owned, and since it does not depreciate, this concept was not taken into account as a cost. A steady-state LCC was used [22]; that is, no discount rate was applied since the objective of this work was not to evaluate the profitability of investment projects.

2.4.1. Fixed Costs

The fixed costs correspond to the costs linked to the amortization of assets. The straight-line method was used to calculate amortization. The final cost of each concept, expressed in $EUR \cdot ha^{-1} \cdot year^{-1}$ and in $EUR \cdot kg^{-1} \cdot year^{-1}$, includes its opportunity cost.

In the conventional Fino and Verna models, the investments to be made differ little due to their similarity (crop area, plant spacing, plant material, etc.). The investments include all the infrastructure necessary for irrigation: irrigation equipment, irrigation network, and irrigation reservoir. The reservoir is sized to store half of the water required in the month with maximum water requirements. For the sizing of the irrigation equipment, the flow required by the emitters per unit area and the size of the farms are taken into account. The irrigation network is sized in the same way, with polyethylene pipes (with diameters of 63 mm and 16 mm) and 4 $L \cdot h^{-1}$ (6 drippers per plant) self-compensating drippers. The investments also include a warehouse for irrigation equipment and tools, various materials (hoes, secateurs, etc.), the preparation of the land, and planting. Preparation and planting include the following tasks: uprooting or lifting with a moldboard, collecting the remains of the previous crop, clearing the soil, refining–leveling and forming plateaus, and the planting of grafted nursery plants. Plateaus are widespread in lemon cultivation. They prevent the trees from being exposed to continuous humidity, thus protecting them against the attack of fungi such as *Phytophtora*.

2.4.2. Variable Costs

The variable costs are those that can vary in the short term, that is, from one production cycle to another. Machinery was considered a variable cost since it is common for farms to use their machinery for other crops or for it to be used sporadically on other farms. For this reason, market prices were used for the contracting of services.

Below, the necessary means are explained for each production cycle when the plantation has reached its adult state. For the development years, the means were calculated by applying a coefficient to the costs associated with adult trees; these years in development were taken into account in the compensated unit cost. All the final costs of the production factors of each model have their corresponding opportunity cost incorporated. The cost of harvesting was not included since it was paid for by the buyer.

- Crop insurance

In the case of lemon, the most common coverage is hail. The cost of insurance was calculated from the report "Coste Medio del Seguro en la Comunidad Autónoma de Murcia" written by Agroseguro.

- Pruning

The lemon tree is vigorous and annual manual pruning is widespread. The pruning section corresponds to the cost associated with the labor used in this work. After pruning, the wood is shredded and incorporated into the soil.

- Machinery

This includes the use of machinery and tools in activities such as phytosanitary treatments, herbicide treatments, etc. It was considered that farms hire external services to carry out the work. The cost of machinery was accounted for through the market unit cost: tractor + implement + labor.

- Fertilizers

The balance used for citrus trees is 3-1-2 ($N\text{-}P_2O_5\text{-}K_2O$) [48]. The needs, in fertilizer units ($N\text{-}P_2O_5\text{-}K_2O\text{-}CaO\text{-}MgO$), that were used to establish the fertilizer programs were 190-70-140-20-10 in conventional Fino and 160-60-100-15-8 in conventional Verna. These quantities were set based on the information extracted from the surveys, taking into account the optimal balance of the lemon tree described in the fertilization programs recommended by MAGRAMA [48] as well as information from regional publications [31,44]. Liquid inorganic fertilizers, iron chelates, and humic + fulvic acids are applied through fertirrigation. Foliar application is used for zinc and manganese chelates as for amino acids.

- Phytosanitary treatments

Phytosanitary treatments vary annually and from one farm to another due to various agro-climatic factors, although based on the survey data, an average treatment program can be established for each of the models. The most common and serious pests for adult trees in the SE of Spain are usually *Aspidiotus nerii*, *Tetranychus urticae*, *Panonychus citri*, and *Prays citri* [31,42,49]. The most common practice is to carry out three annual treatments and one biotechnological control treatment.

- Herbicides

Two annual treatments are carried out. To apply herbicide, a tank is used to which two sprayers are attached; with these, two operators spray both rows of each lane. The herbicide used is glyphosate. Between the rows, it is common to carry out superficial tillage with a tractor and cultivator.

- Maintenance

The maintenance cost was obtained as a percentage (1.50%) of the cost of the fixed assets: warehouse, irrigation network, irrigation equipment, and reservoir.

- Permanent staff

The owner of the farm usually works on tasks related to its management, including the acquisition of inputs, programming irrigation and fertilization, contracting external services such as pruning, etc. This is reflected as a cost in hours per hectare and year.

- Water (irrigation)

The irrigation programs of Fino and Verna were designed using data from three agrometeorological stations of the SIAM (Agricultural Information System of Murcia: http://siam.imida.es, accessed on 1 August 2024) located in the representative areas for lemon cultivation: CA12 (La Palma), AL52 (Librilla), and MO22 (Molina de Segura). The monthly irrigation allocations were based on average data from the three stations for a period of 5 years. With these data and the information extracted from the surveys, annual water allocations of 5800 $m^3 \cdot ha^{-1}$ for Fino and 5200 $m^3 \cdot ha^{-1}$ for Verna were established.

- Electrical energy (irrigation)

This refers to the energy consumed by the pumps during fertirrigation.

2.5. Environmental Evaluation: Life Cycle Assessment

To carry out the environmental assessment of Fino and Verna production models, LCA was used. The LCA is an environmental assessment methodology that studies the life cycle of a production process and makes it possible to quantify the potential environmental impacts generated and to identify which elements contribute the most to them. It is standardized by the ISO 14040-14044 standards [14,15] and consists of four phases: the definition of objective and scope; inventory; impact analysis; and the interpretation of the results.

2.5.1. Objective and Scope

This LCA aims to evaluate and compare, environmentally, two lemon cultivation models characteristic of the SE of Spain: conventional Fino and conventional Verna. The FU is 1 kg of lemons and the entire analysis was referenced to it. Only the cultivation phase was studied, this being the scope of the analysis and its limit. The use of this FU and the limits of the analysis coincide with those of other LCA works on citrus [26,38,50,51]. As the models analyzed only produced one product (lemons), they were treated as monofunctional systems, and procedures for assigning environmental loads were not applied.

The components taken into account in the models studied were as follows:

- Infrastructure: This corresponds to the investment and fixed assets of the LCC. It includes the fuel and lubricant consumed by the machinery during the preparation and planting of the land and its emissions into the atmosphere; the production process of the seedling in the nursery; the irrigation equipment and the irrigation network, accounting for its raw materials, manufacture, and transportation; the reservoir, taking into account the fuel and lubricant consumed in its construction; the resulting emissions; and the necessary raw materials, their manufacture, and transportation.
- Machinery: the fuel and lubricant consumed by machinery during agricultural work in the production cycle and its emissions.
- Fertilizers: the production of inorganic fertilizers and their transportation, packaging, and emissions into the atmosphere derived from the application of nitrogen fertilizers in the field.
- Pesticides: the production of phytosanitary products and herbicides, their packaging, and transportation.
- Electrical energy: the electrical energy consumed during fertigation.
- Waste treatment: The treatment of infrastructure and packaging (metals and plastics) that have reached the end of their useful life. It was considered that 80% of these materials are recycled and the remaining 20% end up in landfills. Prunings were not considered waste since they are crushed and incorporated into the soil.

The LCA was carried out by accounting for the entire useful life of the crop; therefore, the years of development in which production and inputs vary according to the coefficients set out in Tables 2 and 3 were included. The useful life of the materials was also considered: the reservoir has a 30-year useful life, the irrigation equipment 15 years, and the irrigation network 10 years.

2.5.2. Life Cycle Inventory

The foreground data (Table 1) are based on the information extracted from the surveys and are presented relative to the FU in Table 4. To develop the LCA, the SimaPro 9.5 software (developed by Pré Sustainability) was used; this allows us to work with very extensive databases of inventories and methodologies. The background data (fuel, energy, materials, products, and transport) were extracted from the Ecoinvent 3.8 database, which is widely used in the LCA of agri-food products [24,52–54] and in the citrus sector [30]; it is integrated into the software used.

Iron, zinc, and manganese chelates and amino acids were not taken into account in the analysis since they do not appear in this database, and, in any case, the quantities applied are very low. The same goes for *Bacillus thuringiensis* and *Neoseiulus californicius*.

Emissions to the atmosphere due to the consumption of diesel by agricultural machinery were estimated using the emission factors established by EEA [55]. Emissions to the atmosphere derived from the application of nitrogen fertilizers to agricultural soil were calculated based on the guidelines of IPCC [56] and EEA [55]: NH_3 and NO_2 [55], and the direct and indirect emissions of N_2O [56]. The leaching of nitrate and phosphates was not taken into account since IPCC [56] indicates that the leached fraction can be considered zero in cultivated areas with warm climates and where drip irrigation is carried out.

2.5.3. Impact of the Life Cycle: Evaluation and Interpretation

To determine the magnitude and significance of potential environmental impacts, the CML-IA Baseline 4.7 midpoint evaluation methodology was used (available in SimaPro). This methodology is widely used for the evaluation of impacts in the agri-food field [4,6,57–61] and, in particular, in the citrus sector [30]. CML-IA Baseline 4.7 contemplates 11 impact categories: abiotic depletion (AD), abiotic depletion fossil fuels (ADFFs), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), fresh water aquatic ecotoxicity

(FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (A), and eutrophication (E).

Table 4. Life cycle inventory of primary data of Fino and Verna in relation to the FU: 1 kg of lemons.

	Fino Conventional	Verna Conventional
INFRASTRUCTURE		
Preparation and planting		
Diesel (g·kg^{-1})	0.2072	0.2550
Lubricant oil (g·kg^{-1})	0.0002	0.0003
Manure (kg·kg^{-1})	0.0151	0.0186
Local transportation (kg·km·kg^{-1})	0.7538	0.9277
Irrigation reservoir		
Diesel (g·kg^{-1})	0.3396	0.5016
Lubricant oil (g·kg^{-1})	0.0004	0.0005
HDPE sheet (g·kg^{-1})	0.1164	0.1719
Local transportation (kg·km·kg^{-1})	0.0058	0.0086
Irrigation equipment		
Iron (mg·kg^{-1})	8.3754	12.3689
Steel (mg·kg^{-1})	0.8375	1.2369
Copper (mg·kg^{-1})	2.5126	3.7107
Brass (mg·kg^{-1})	0.1675	0.2474
PVC pipe (mg·kg^{-1})	6.7003	9.8951
LDPE pipe (mg kg^{-1})	0.3350	0.4948
Polyamide (mg·kg^{-1})	0.5025	0.7421
HDPE tanks (mg·kg^{-1})	7.5378	11.1320
Local transportation (kg·km·kg^{-1})	0.0013	0.0020
Irrigation network		
LDPE (g·kg^{-1})	0.4336	0.6403
Local transportation (kg·km·kg^{-1})	0.0217	0.0320
INPUTS/SUPPLIES		
Agricultural machinery		
Diesel (g·kg^{-1})	2.6055	3.6819
Lubricant oil (g·kg^{-1})	0.0028	0.0040
Fertilizers		
Phosphoric acid (g·kg^{-1})	3.0767	3.8954
Ammonium nitrate (g N·kg^{-1})	0.7892	1.0130
Urea ammonium nitrate (g N·kg^{-1})	2.2653	2.8124
Potassium nitrate (g N·kg^{-1})	0.9641	1.2208
Calcium nitrate (g N·kg^{1})	0.2891	0.3213
Magnesium nitrate (g N·kg^{-1})	0.2704	0.3190
Humic and fulvic acids (g N·kg^{-1})	0.0245	0.0241
Local transportation (kg·km·kg^{-1})	1.0275	1.3360
Pesticides		
Paraffin oil (83%) (g·kg^{-1})	1.1387	1.6816
Spirotetramat (10%) (g·kg^{-1})	0.0041	0.0091
Piriproxifen (10%) (g·kg^{-1})	0.0034	0.0051
Hexitiazox (10%) (g·kg^{-1})	0.0014	0.0020
Glyphosate (g·kg^{-1})	0.0659	0.0972
Local transportation (kg·km·kg^{-1})	0.0936	0.1383
Irrigation		
Electricity (kwh·kg^{-1})	0.0163	0.0216

To interpret the results, a contribution analysis was carried out to calculate the percentage contribution of each of the components to each impact category analyzed. In addition, the global/overall contribution was also used [24], which indicates the percentage contribution of each component to the global environmental impact generated by the model.

2.6. Sensitivity Analysis

Finally, a sensitivity analysis was carried out, introducing variability in two components:

The water mix for irrigation. In the SE of Spain, the water supply comes from various sources (underground, surface, desalinated, Tajo-Segura transfer, and reused) and differs greatly from one area to another [62]. Likewise, there is great year-to-year variability depending on the weather conditions. In the economic analysis, the unit price of the water used corresponded to the Irrigation User Community "Campo de Cartagena", which is the most important at a territorial level in the SE of Spain (irrigable area of 42,255 hectares). The water price variable has a high economic relevance in the cost structure (Table 5). For this reason, it was introduced in the sensitivity analysis, taking into account that the consumption and prices of the different waters are changeable, with an upward evolution in price. In the LCA, the energy necessary for water extraction depending on its origin was not considered due to the volatility of this variable and because in most works of this nature, regardless of the location or the agricultural product [22,24,26,27,51,63], it is not taken into account due to the lack of such specific data. The water mix of the Irrigation User Community "Campo de Cartagena" is in the order described by Martín Gorriz et al. [62] (surface: 19.8%, groundwater 23.4%, reused: 7.6%, transfer: 32.2%, and desalinated: 17.0%), although—as has been highlighted—it is changeable. The models are analyzed from an environmental perspective, including the energy necessary for the extraction of water at the source based on the different extraction sources (S2). Now, as the same author indicated, the critical situation of water availability in Spain, and specifically in the SE, is causing reductions in the concessions of the Tajo–Segura transfer, with the consequent increase in the contribution of desalinated water. For this reason, the most unfavorable scenario proposed by Martín Gorriz et al. [62] and García García and García García [64], in which the transfer is completely replaced by desalinated water (49.2% of the total mix), was also analyzed from the economic (S1) and environmental (S3) viewpoints.

Emissions form pesticide application. Many LCA studies do not consider emissions from pesticide application, usually due to the lack of a clear, simple, and standardized methodology [6]. For this reason, in this study, emissions from pesticides (phytosanitary products and herbicides) were not taken into account. Although, two scenarios were proposed to see what would happen if they were incorporated: (1) using the default emission fractions suggested by the PestLCI consensus V.1.0 for the different environmental compartments (air, agricultural land, crop, and non-agricultural surfaces—freshwater and natural soil) [65], taking into account the specific case of citrus and the type of active ingredient used (available spreadsheet online at: https://orbit.dtu.dk/en/projects/olca-pest, accessed on 1 August 2024) (S4) and (2) following the EU recommendations by applying fixed emission factors (90% soil, 9% air, and 1% water) (S5) [66].

The results of the analysis of the different scenarios were evaluated with the relative difference in the different economic and environmental indices, expressed as RD (%) = $100 \times (S0 - Sn)/S0$, with Sn being each of the defined scenarios and S0 being the initial model analyzed.

Table 5. Cost structure. The absolute annual costs in EUR·ha^{-1}, and the relative costs in relation to the total costs (%).

	Fino Conventional		Verna Conventional	
	Absolute Annual Costs (EUR·ha^{-1})	**Relative Costs (%)**	**Absolute Annual Costs (EUR·ha^{-1})**	**Relative Costs (%)**
Fixed costs (FCs)				
Warehouse for equipment	41	0.42%	41	0.45%
Preparation and planting	144	1.49%	126	1.39%
Irrigation reservoir	86	0.89%	75	0.83%
Irrigation equipment	89	0.92%	89	0.98%
Irrigation network	193	2.00%	193	2.13%
Various materials	25	0.26%	25	0.28%
Total fixed costs	***578***	***5.98%***	***549***	***6.07%***
Variable costs (VCs)				
Insurance	747	7.73%	522	5.77%
Pruning	1131	11.70%	1028	11.36%
Machinery	650	6.72%	630	6.96%
Fertilizers	1014	10.49%	855	9.45%
Phytosanitary products	504	5.21%	504	5.57%
Biotechnological products	330	3.41%	488	5.39%
Herbicides	57	0.59%	57	0.63%
Maintenance of infrastructure	125	1.29%	118	1.30%
Irrigation energy	196	2.03%	175	1.93%
Irrigation water	2060	21.31%	1847	20.41%
Permanent staff	2276	23.54%	2276	25.15%
Total variable costs	***9090***	***94.02%***	***8500***	***93.93%***
Total costs (TCs)	***9668***	***100.00%***	***9049***	***100.00%***

	Fino Conventional	Verna Conventional
Gross lemon cost * (EUR·kg^{-1})	***0.210***	***0.292***
Fresh lemon cost ** (EUR·kg^{-1})	***0.263***	***0.352***
Compensated gross lemon cost * (EUR·kg^{-1})**	***0.222***	***0.307***
Compensated fresh lemon cost ** (EUR·kg^{-1})**	***0.278***	***0.370***

Gross lemon cost * (EUR·kg^{-1}): gross cost per kilo of total lemons produced in the adult state. **Fresh lemon cost ** (EUR·kg^{-1}):** cost per kilo of fresh lemons (discounting lemons intended for industry) produced in the adult state. **Compensated gross lemon cost *** (EUR·kg^{-1}):** cost per kilo of total lemons taking into account the entire useful life. **Compensated fresh lemon cost **** (EUR·kg^{-1}):** cost per kilo of fresh lemons (discounting lemons intended for industry) taking into account the entire useful life.

3. Results and Discussion

3.1. Economic Evaluation: Life Cycle Cost Analysis

Investment is a significant section for all the irrigated fruit trees due mainly to the cost of the irrigation installation (reservoir, irrigation network, and irrigation equipment) (Tables A1 and A2 from Appendix A). Within the irrigated fruit group, citrus trees in general and lemon trees in particular usually require a lower investment than stone fruit trees such as peaches or plums, since the latter have higher planting costs [67]. Stone fruit trees are often subject to the payment of royalties, which increases the price of the seedling by around 30–40% compared to that of citrus trees. They also have a higher planting density, with a greater number of trees per hectare. Despite being able to have longer useful lives, constant varietal renewal, driven by changing commercial market requirements, leads to the rapid obsolescence of stone fruit plantations, reducing their useful life to less than 15 years. This further increases the cost of this item per hectare. In the case of Fino and Verna lemons, the investments are practically identical due to the similarity of the crop, plant material, planting scheme, irrigation network, etc.

Regarding the cost structure (Table 5), fixed assets are relatively low, representing only 6% of the total annual costs, which is in line with other works on citrus in the Mediterranean area [26,67,68]. This is because it is a woody crop with long useful lives (25 and 30 years in Fino and Verna, respectively), which reduces the impact of the investment, as it allows for a lower, gradual amortization. The most important fixed cost corresponds to the irrigation system, which represents just over 60% of the fixed costs.

In both crops, the most relevant costs are, by order of magnitude, the variable costs linked to labor (pruning, permanent staff, and labor associated with the use of agricultural machinery) and irrigation (water and electricity), followed by fertilizers and sanitary products (phytosanitary and biotechnological). Other works on citrus fruits also identified these components as the most significant in the cost structure [26,32,67,68]. In Fino, they represent 3631 EUR·ha^{-1}, 2256 EUR·ha^{-1}, 1014 EUR·ha^{-1}, and 834 EUR·ha^{-1}, respectively (38%, 23%, 10%, and 9%, respectively, of the total production cost, TC). In Verna, they are in the same order: 3523 EUR·ha^{-1} (40% of the TC), 2022 EUR·ha^{-1} (22%), 855 EUR·ha^{-1} (9%), and 992 EUR·ha^{-1} (11%) (Table 5). These values are slightly higher in Fino due to its greater vigor and productivity, which translates into a greater consumption of inputs. In any case, Fino is more efficient than Verna in the use of irrigation and fertilization, with the cost being 0.052 EUR·kg^{-1} (gross compensated) and 0.023 EUR·kg^{-1}, respectively, while in Verna it is 0.068 EUR·kg^{-1} and 0.029 EUR·kg^{-1} in this same order. In recent years, fertilization has evolved to better suit the specific needs of crops, mainly due to the high costs of fertilizers. This evolution also reflects the growing concern with regard to reducing nutrient leaching and immobilization in the soil. These changes are in line with European policies—such as Council Directive 91/676/EEC, which seeks to address nitrate pollution arising from agricultural activities. This reduction in fertilization can be verified by comparing the current balances (Fino: 190-70-140-20-10 and Verna: 160-60-120-15-8) extracted from the surveys with the recommendations from previous years—such as that of MAGRAMA [48], which established maximum doses for lemon trees of 240-80-140.

The costs associated with labor are the most relevant, even though the case of lemon is very particular in this aspect since it is one of the few crops in which the harvesting is the responsibility of the buyer and, therefore, is not included in the cost structure. If this were accounted for (harvesting and loading onto trucks), the items associated with labor would account for up to 59% (8691 EUR·ha^{-1}) and 56% (6933 EUR·ha^{-1}) of the total costs in Fino and Verna, respectively. The harvest cost is 0.11 EUR·kg^{-1}. In terms of employment, Fino and Verna generate 0.18 gross-compensated AWU·ha^{-1}·year^{-1}; with the inclusion of harvesting the figure rises to 0.34 gross-compensated AWU·ha^{-1}·year^{-1} (632 h·ha^{-1}) in Verna and 0.43 gross-compensated AWU·ha^{-1}·year^{-1} (786 h·ha^{-1}) in Fino (1 Agricultural Work Unit is equivalent to 1840 h). Thus, they have a more marked social character in relation to other crops such as olive and almond trees in the SE of Spain [69]. These results for Verna are very similar to those obtained by Pergola et al. [26] for Feminello lemon (696 h·ha^{-1}), although the latter has a denser planting scheme and lower production per unit area. Sgroi et al. [32] indicated that in Feminello lemon with planting densities identical to those in this work, 338 h·ha^{-1} are required, a value very far from that obtained in this study, which may be due to the lower productivity (22,872 kg·ha^{-1}).

Irrigation is the second most relevant input in terms of costs. The SE of Spain is a semi-arid area where water is a limiting factor due to its low availability and high price [24,31,35]. The evolution of water availability and cost in recent years in this area indicates a continuous increase in its importance within the cost structure. In 2018, the average price was 0.22 EUR·m^{-3} [67], while it is currently 0.35 EUR·m^{-3}, an increase of 63%. In this area, the water supply comes from various sources, and this increase in the price of water is closely related to an increase in dependence on desalinated water, which entails higher costs from economic and environmental perspectives [62].

In conventional lemon cultivation, there has been a continuous increase in the use of biotechnological pest control due to the reduced availability of legal active ingredients and the additional benefits it offers, such as the maintenance of auxiliary fauna and the lower resistance of pests to the chemical products. However, its use is still not the majority position. It is important to highlight that in Verna, the cost of biotechnological pest control is slightly higher since it is more sensitive to *Prays citri* than Fino, given its greater reflorescence and, therefore, its greater sensitivity by temporal extension.

As Table 5 indicates, the unit production cost is higher in Verna than in Fino, which is due to its lower productivity, since the input consumption and investment are very similar for the two varieties. However, normally, this difference in cost is compensated by a higher market price for Verna [12]. The compensated fresh lemon costs are much higher than the gross costs since the high non-marketable fresh fraction (that is being imposed on the sector) is discounted and the years prior to full production are taken into account, during which costs are incurred but the production is lower.

3.2. Environmental Evaluation: Life Cycle Assessment

Verna has higher absolute values than Fino in all the impact categories (Table 6), with the superiority of the categories varying by 25–32%. This is due to its lower productivity (31,000 kg vs. 46,000; a difference of 33%), although in Fino and Verna, the overall contribution of the system components to environmental impacts is practically identical (Table 6 and Figure 2). This is because they are very similar regarding infrastructure and inputs, differing mainly in their productivity. Table 6 and Figure 2 show that fertilizers are the component of the system with the greatest overall contribution to environmental impacts (73% in Fino and 71% in Verna). This is fundamentally linked to the process of the production of synthetic fertilizers, which accounts for approximately 81% of the global contribution of fertilizers, while the remaining 19% corresponds to the emissions derived from the application of nitrogen fertilizers to the soil. In line with these results, Pergola et al. [26] pointed out that in conventional lemons, fertilizers are the element with the greatest contribution to the impacts, which is transferable to the general case of citrus fruits [25,30]. Likewise, for other agricultural products, they are also usually identified as hotspots [53,70]. In the present work, the contribution of the rest of the components is very low. After the fertilizers come the infrastructure, machinery, and energy used in fertigation. Their contributions are very similar, ranging between 7% and 10% for both Fino and Verna. The production of pesticides (phytosanitary products and herbicides) makes a contribution of less than 5%, and waste treatment has a negative contribution since recycling accounts for 80% of the total plastics and metals used in the production process.

Fertilizer production makes contributions greater than 50% in all the impact categories (Table 6 and Figure 2), except in A and E, where emissions due to the application of fertilizers in the field predominate (52% and 60%, respectively, in Fino and Verna). These two categories are mainly affected by the release of NH_3 emissions, and other studies [26] highlight NH_3 emissions as a critical point in A. In the AD, HT, FWAE, and MAE categories, fertilizer production makes the highest contributions, varying from 71% to 82% depending on the category and variety. The critical points are the production of potassium nitrate and urea ammonium nitrate, except in MAE, for which the production of phosphoric acid is the most influential.

The contributions of fertilizer production for Fino and Verna are, respectively: 59% and 56% to ADFF, 51% and 49% to GW, and 55% and 51% to OLD. Pergola et al. [26] also showed that for conventional lemon, fertilizer production is the component with the greatest weight in GW, which coincides with the findings of Ribal et al. [25] and SanJuan et al. [71] for the cultivation of oranges in the SE of Spain. In addition to the production of fertilizers, in ADFF and OLD agricultural machinery has a significant weight (18–30%), derived from the diesel production process. Cabot et al. [27] found the contributions of fertilizer production to ADFF and OLD of 57% and 82%, respectively, and for ADFF, they indicated machinery as the component with the second highest contribution, similar to the results of this study. For GW, agricultural machinery and emissions due to nitrogen fertilizer use in the field are also relevant. In the case of machinery, this is mainly due to the emissions derived from the combustion of diesel (representing 86% of its total contribution), mainly CO_2. The impact of the emissions arising from nitrogen fertilizer use in the field stands out due to the release of N_2O, coinciding with the findings of Cabot et al. [27].

Table 6. Characterization of the potential environmental impacts and contributions of the components of the system in the conventional Fino and Verna. FU: 1 kg of lemons.

Impact Category	Absolute Values	Infrastructure	Machinery	Energy	Fertilizer Production	Fertilizer Emissions	Pesticides	Waste Treatment
Fino Conventional					**Contributions (%)**			
AD (kg Sb-eq)	6.89×10^{-7}	11.42	0.21	2.41	81.94	0.00	4.94	−0.91
ADFF (MJ)	7.73×10^{-1}	10.29	17.81	8.00	59.05	0.00	9.05	−4.18
GW (kg CO_2-eq)	6.30×10^{-2}	8.10	15.42	8.30	50.68	16.12	2.47	−1.10
OLD (kg CFC-11-eq)	6.48×10^{-9}	8.25	27.99	4.43	54.63	0.00	4.89	−0.18
HT (kg 1,4-DB-eq)	4.64×10^{-2}	8.38	1.60	6.26	79.55	0.54	4.29	−0.61
FWAE (kg 1,4-DB-eq)	2.21×10^{-2}	9.56	1.07	11.31	73.24	0.00	4.70	0.12
MAE (kg 1,4-DB-eq)	8.31×10^{1}	3.40	0.92	10.61	82.17	0.00	2.97	−0.06
TE (kg 1,4-DB-eq)	1.79×10^{-4}	17.71	6.43	13.52	57.51	0.00	4.71	0.12
PO (kg C_2H_4-eq)	2.12×10^{-5}	6.79	4.80	6.81	55.89	24.31	2.72	−1.30
A (kg SO_2-eq)	1.02×10^{-3}	9.90	1.65	3.82	31.78	52.14	0.93	−0.21
E (kg PO_4-eq)	2.17×10^{-4}	11.37	1.04	4.09	20.79	60.23	2.20	0.29
Overall contribution (%)		**9.56**	**7.18**	**7.23**	**58.84**	**13.94**	**3.99**	**−0.73**
Verna conventional								
AD (kg Sb-eq)	8.81×10^{-7}	12.74	0.23	2.49	79.24	0.00	6.35	−1.05
ADFF (MJ)	1.01×10^{0}	11.07	19.19	8.07	56.14	0.00	10.22	−4.70
GW (kg CO_2-eq)	8.10×10^{-2}	8.54	16.95	8.54	48.87	15.49	2.87	−1.26
OLD (kg CFC-11-eq)	8.60×10^{-9}	8.43	29.81	4.41	51.42	0.00	6.12	−0.20
HT (kg 1,4-DB-eq)	5.87×10^{-2}	9.35	1.79	6.55	77.98	0.52	4.52	−0.71
FWAE (kg 1,4-DB-eq)	2.81×10^{-2}	10.23	1.18	11.75	71.19	0.00	5.51	0.14
MAE (kg 1,4-DB-eq)	1.06×10^{2}	3.71	1.02	11.00	80.87	0.00	3.46	−0.06
TE (kg 1,4-DB-eq)	2.30×10^{-4}	17.96	7.07	13.91	55.46	0.00	5.46	0.13
PO (kg C_2H_4-eq)	2.70×10^{-5}	7.36	5.32	7.06	55.09	23.55	3.12	−1.50
A (kg SO_2-eq)	1.28×10^{-3}	9.88	1.86	4.02	31.81	51.63	1.05	−0.24
E (kg PO_4-eq)	2.73×10^{-4}	11.37	1.17	4.31	20.58	59.66	2.57	0.34
Overall contribution (%)		**10.06**	**7.78**	**7.47**	**57.15**	**13.71**	**4.66**	**−0.83**

Abiotic depletion (AD), abiotic depletion fossil fuels (ADFFs), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (A), and eutrophication (E).

In TE and PO, fertilizer production contributes 58% and 56% in Fino and 56% and 55% in Verna (Figure 2), respectively, essentially due to phosphoric acid production. In TE, the rest of the impact is distributed mainly among irrigation, infrastructure, and machinery, while in PO, the emissions due to fertilizer use in the field are notable (24% in both Fino and Verna).

According to Cabot et al. [30], global warming potential is the impact category used most in LCA studies on citrus fruits, which also occurs in the LCA of agri-food products [61,72]. Its relevance as an environmental problem has also generated a high social awareness. Therefore, it was used as a reference to validate the results of this study. In this work, the GW values (0.063 kg CO_2-eq·kg in Fino and 0.081 kg CO_2-eq·kg in Verna) (Table 6) are close to the range of values (0.093–0.300 kg CO_2-eq·kg) observed in the LCAs of conventional lemons [4,26,27,62,63], although they are slightly lower. Also, they are close to, but slightly below, the range of values (0.089–0.310 kg CO_2-eq·kg) recorded for other citrus fruits, such as oranges and mandarins [4,26,50,51,71,73,74]. This may be due to several reasons, among which are the following: (1) The high yields of lemon production systems in Spain, especially in the case of Fino (46,000 kg·ha^{-1}). (2) The use of lower amounts of pesticides than in other, damper places where there is a greater incidence of fungal diseases. In addition, the use of active ingredients is lower due to a greater use of biotechnological control. (3) The application of N_2O emission factors adjusted to arid areas [56]. (4) The lesser use of machinery, since fresh lemon production does not allow the mechanization of tasks as significant as pruning.

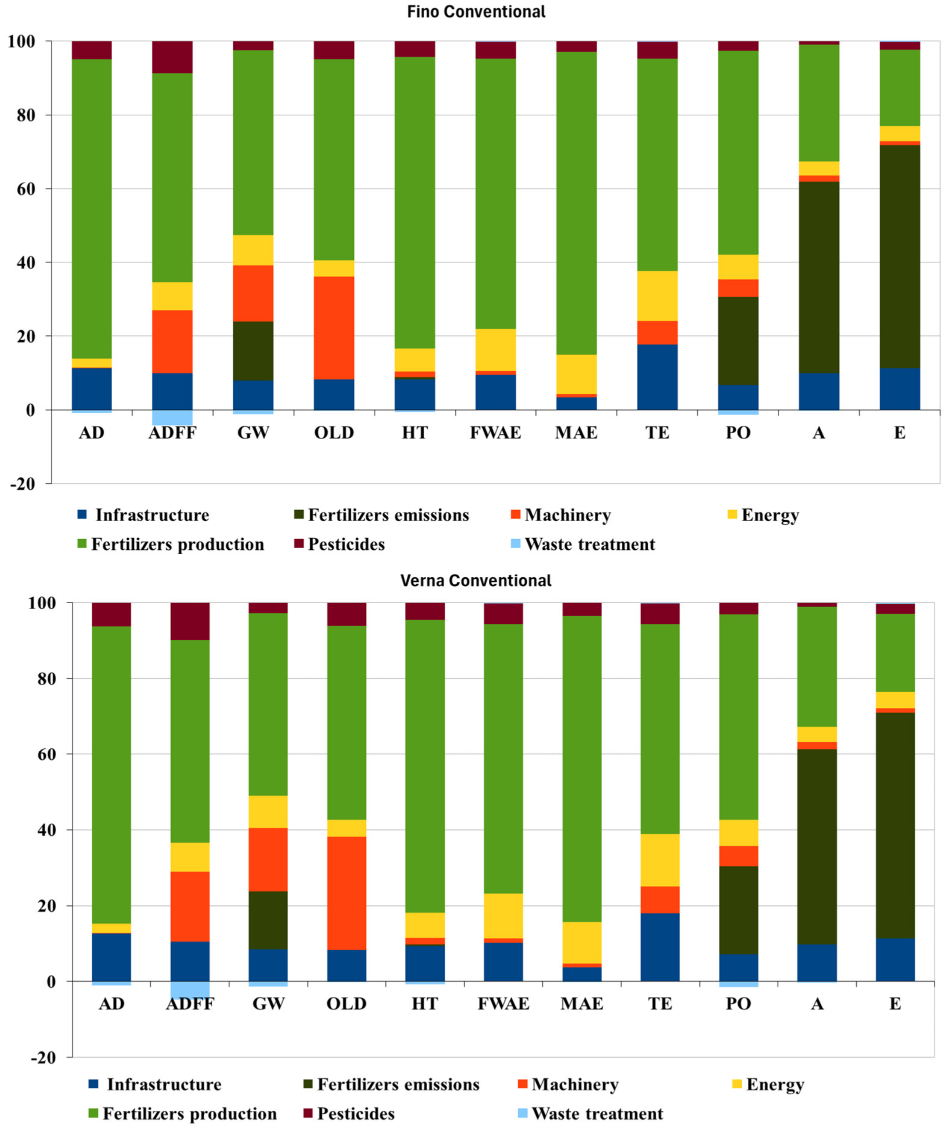

Figure 2. Contributions of the system components to the potential environmental impacts caused by the models of production of Fino and Verna lemons. Abiotic depletion (AD), abiotic depletion fossil fuels (ADFFs), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (A), and eutrophication (E).

Cabot et al. [27], working in Uruguay, obtained 0.093 kg CO_2-eq·kg, a lower value and close to those of this study (Table 6). The low impact of the Uruguayan lemon could be largely due to its high productivity (56 tonnes·ha^{-1}). Its higher density of trees per hectare, annual rainfall up to three times higher than that of this area (1100 mm vs. 308 mm), and high mechanization of agricultural work (pruning and harvesting) promote high productivity, in turn reducing the environmental impact expressed per unit of mass. Nonetheless, its productivity entails a greater consumption of nitrogen fertilizers (203 kg·ha^{-1} vs. 190 kg·ha^{-1} in Fino and 160 kg·ha^{-1} in Verna), which are directly related to greenhouse gas emissions. Furthermore, in these more humid conditions, greater quantities of fungicides are required to control diseases and pests. Likewise, the N_2O emission factors for nitrogen fertilizers proposed by IPCC [56] are higher for these more humid areas

(0.016 kg N_2O-N·kgN^{-1} vs. 0.005 kg N_2O-N·kg N^{-1}) and also account for indirect N_2O emissions from nitrate leaching, which can be considered null in arid climates with high-frequency drip irrigation, as is the case for lemon cultivation in the SE of Spain. This would also explain why fertilizer emissions were the component with the greatest contribution to GW (55%) in the study by Cabot et al. [27], in contrast to the great relevance of fertilizer production in this study. Machin Ferrero et al. [63] calculated a value of 0.196 kg CO_2-eq·kg for GW, and, as in the work of Cabot et al. [27], field emissions from fertilizers were the main hotspot in this category. This is possibly related to the use of an N_2O emission factor 13 times higher than that used in this study. In the work of both Cabot et al. [27] and Machin Ferrero et al. [63], active ingredients that are currently prohibited in EU citrus production were used, such as abamectin. In any case, distinct LCA studies on the same product do not take into account the same factors or apply the same characterization methods, leading to differences in the results. The higher values in Uruguay may be due, in addition to these aspects, to the inclusion of the harvest. Pergola et al. [26] reported slightly higher values of GW (0.12 kg CO_2-eq·kg) for a latitude (Sicily) similar to that of this study. This discrepancy could be attributable, among other factors, to (1) lower productivity (30 t·ha^{-1}), (2) the use of phytosanitary products (such as chlorpyrifos) permitted at the time but currently prohibited in the EU due to their possible negative impacts on the environment and human health, and (3) the greater use of agricultural machinery during the annual production cycle and, therefore, greater diesel consumption compared to this work (659 kg·ha^{-1} vs. 139 kg·ha^{-1}).

3.3. Sensitivity Analysis

In the economic evaluation of Fino and Verna, irrigation (water and energy destined for fertigation) is the second most economically important item in the cost structure, representing 23% of the total costs in Fino and 22% in Verna. The water price considered was 0.35 EUR·m^{-3} and corresponds to the mixture of the Irrigation User Community “Campo de Cartagena” described by Martín-Gorriz et al. [62]. A scenario (S1) was proposed where the water contributions from the transfer are eliminated and replaced by desalinated water, with the price of water for this mixture being 0.508 EUR·m^{-3}. In this case, the irrigation item (water and energy for fertigation) rises to 3187 EUR·ha^{-1} and 2856 EUR·ha^{-1} in Fino and Verna, respectively (30% and 29% of the TC, respectively). The compensated fresh lemon cost becomes 0.305 EUR·kg^{-1} in Fino and 0.404 EUR·kg^{-1} in Verna, that is, an increase of around 9% compared to the current scenario. This increase raises the total costs and could put the economic viability of the crop at risk (Table 7).

Table 7. Sensitivity analysis of the total costs.

Scenarios	Fino	Verna
Total costs (EUR ha^{-1})		
S0 (conventional)	9668	9049
S1	10,599	9883
Relative difference * (%)		
S0 vs. S1	−9.63	−9.22

* RD = 100 × (S0 − Sn)/S0.

As indicated in Section 2.6, in the environmental evaluation, the current scenario does not consider the energy required for water extraction according to its origin. If the energy necessary for extraction is computed according to the current extraction sources (S2)—surface 19.8%, groundwater 23.4%, reused 7.6%, transfer 32.2%, and desalinated 17.0%—the impacts in all the categories increase considerably (27–159%) (Tables 8 and 9). The categories with the greatest increases are related to toxicity (FWAE, MAE, and TE). The inclusion of the energy necessary for water extraction not only affects significantly the different categories, but also makes irrigation the component with the largest overall contribution to them. This suggests the need to incorporate this energy into the analyses so that they are more precise and adjusted to reality. In this sense, it is crucial that the organizations in charge of water management provide transparent and accessible data. However, the values of the impact categories could be reduced if the proportion of renewable energy in the Spanish electricity mix increased to the detriment of non-renewable energy, which contributes significantly to the impacts, as is the case of coal, which has a considerable effect on the impact of the national mix. Scenario S3 accounts for the energy necessary to extract water, but it is a future scenario in which the transfer water is replaced by desalinated water. In S3, the impacts in all the categories increase even more than in S2, with the RD ranging between 46% and 272% (Tables 8 and 9). This increase is due to what was mentioned previously and the fact that desalination consumes 3.5 times more energy per unit volume than transfer [62].

Table 8. Lemon Fino. Values of the potential environmental impacts (PEIs) of the scenarios proposed in Section 2.6 and the relative difference (RD) between the current scenario (S0) and those proposed (Sn).

Lemon Fino PEI	**Scenario 0 (S0)**	**Scenario 2 (S2)**	**Scenario 3 (S3)**	**Scenario 4 (S4)**	**Scenario 5 (S5)**
AD (kg Sb-eq)	6.89×10^{-7}	8.76×10^{-7}	1.01×10^{-6}	6.89×10^{-7}	6.89×10^{-7}
ADFF (MJ)	7.73×10^{-1}	1.47×10^{0}	1.96×10^{0}	7.73×10^{-1}	7.73×10^{-1}
GW (kg CO2-eq)	6.30×10^{-2}	1.22×10^{-1}	1.63×10^{-1}	6.30×10^{-2}	6.30×10^{-2}
OLD (kg CFC-11-eq)	6.48×10^{-9}	9.72×10^{-9}	1.20×10^{-8}	6.48×10^{-9}	6.48×10^{-9}
HT (kg 1,4-DB-eq)	4.64×10^{-2}	7.92×10^{-2}	1.02×10^{-1}	4.64×10^{-2}	4.64×10^{-2}
FWAE (kg 1,4-DB-eq)	2.21×10^{-2}	5.03×10^{-2}	7.00×10^{-2}	2.25×10^{-2}	2.32×10^{-2}
MAE (kg 1,4-DB-eq)	8.31×10^{1}	1.82×10^{2}	2.52×10^{2}	8.31×10^{1}	8.31×10^{1}
TE (kg 1,4-DB-eq)	1.79×10^{-4}	4.52×10^{-4}	6.42×10^{-4}	1.85×10^{-4}	1.85×10^{-4}
PO (kg C2H4-eq)	2.12×10^{-5}	3.75×10^{-5}	4.89×10^{-5}	2.12×10^{-5}	2.12×10^{-5}
A (kg SO2-eq)	1.02×10^{-3}	1.47×10^{-3}	1.77×10^{-3}	1.02×10^{-3}	1.02×10^{-3}
E (kg PO4-eq)	2.17×10^{-4}	3.18×10^{-4}	3.88×10^{-4}	2.17×10^{-4}	2.17×10^{-4}
Relative Difference (%)		**S0 vs. S2**	**S0 vs. S3**	**S0 vs. S4**	**S0 vs. S5**
AD		−27.21	−46.21	-	-
ADFF		−90.31	−153.45	-	-
GW		−93.70	−159.24	-	-
OLD		−49.98	−84.92	-	-
HT		−70.71	−120.13	−0.0017	−0.0020
FWAE		−127.49	−216.71	−1.8851	−4.9225
MAE		−119.56	−203.25	−0.0003	−0.0001
TE		−152.30	−258.91	−3.1766	−3.3457
PO		−76.86	−130.61	-	-
A		−43.65	−73.90	-	-
E		−46.40	−78.72	-	-

Abiotic depletion (AD), abiotic depletion fossil fuels (ADFFs), global warming (GW), ozone layer depletion (OLD), human toxicity (HT), fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (A), and eutrophication (E).

Likewise, it was considered what would happen if the emissions derived from the application of pesticide products in the field were included in the LCA, and these were calculated according to the default emissions of citrus fruits proposed by the PestLCI consensus (S4) [65] and according to the fixed emission factors recommended by the EU (S5) [66]. It can be seen that pesticide emissions in the field only affect the toxicity categories: HT, FWAE, MAE, and TE (Tables 8 and 9), although the increases could be considered negligible, with a maximum RD of 6%. Scenario S5 presents slightly higher values, since the EU [66] does not consider that part of the active ingredients remains in the plant itself but assumes it is completely emitted to the three natural compartments: soil, air, and water.

Table 9. Lemon Verna. Values of the potential environmental impacts (PEIs) of the scenarios proposed in Section 2.6 and the relative difference (RD) between the current scenario (S0) and those proposed (Sn).

Lemon Verna PEI	Scenario 0 (S0)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)	Scenario 5 (S5)
AD (kg Sb-eq)	8.81×10^{-7}	1.13×10^{-6}	1.31×10^{-6}	8.81×10^{-7}	8.81×10^{-7}
ADFF (MJ)	1.01×10^{0}	1.95×10^{0}	2.61×10^{0}	1.01×10^{0}	1.01×10^{0}
GW (kg CO2-eq)	8.10×10^{-2}	1.60×10^{-1}	2.16×10^{-1}	8.10×10^{-2}	8.10×10^{-2}
OLD (kg CFC-11-eq)	8.60×10^{-9}	1.29×10^{-8}	1.60×10^{-8}	8.60×10^{-9}	8.60×10^{-9}
HT (kg 1,4-DB-eq)	5.87×10^{-2}	1.03×10^{-1}	1.34×10^{-1}	5.87×10^{-2}	5.87×10^{-2}
FWAE (kg 1,4-DB-eq)	2.81×10^{-2}	6.59×10^{-2}	9.27×10^{-2}	2.87×10^{-2}	2.97×10^{-2}
MAE (kg 1,4-DB-eq)	1.06×10^{2}	2.39×10^{2}	3.34×10^{2}	1.06×10^{2}	1.06×10^{2}
TE (kg 1,4-DB-eq)	2.30×10^{-4}	5.95×10^{-4}	8.55×10^{-4}	2.38×10^{-4}	2.39×10^{-4}
PO (kg C2H4-eq)	2.70×10^{-5}	4.88×10^{-5}	6.44×10^{-5}	2.70×10^{-5}	2.70×10^{-5}
A (kg SO2-eq)	1.28×10^{-3}	1.88×10^{-3}	2.30×10^{-3}	1.28×10^{-3}	1.28×10^{-3}
E (kg PO4-eq)	2.73×10^{-4}	4.07×10^{-4}	5.02×10^{-4}	2.73×10^{-4}	2.73×10^{-4}
Relative Difference (%)		**S0 vs. S2**	**S0 vs. S3**	**S0 vs. S4**	**S0 vs. S5**
AD		−28.44	−48.72	-	-
ADFF		−92.10	−157.74	-	-
GW		−97.47	−166.94	-	-
OLD		−50.38	−86.28	-	-
HT		−74.76	−128.04	−0.0020	−0.0024
FWAE		−134.11	−229.70	−2.1859	−5.7047
MAE		−125.55	−215.02	−0.0003	−0.0001
TE		−158.83	−272.03	−3.6499	−3.8442
PO		−80.60	−138.04	-	-
A		−45.94	−78.69	-	-
E		−49.24	−84.33	-	-

4. Conclusions

In lemon cultivation, inputs are strictly controlled, and the unit costs of lemon are lower than for other fruit trees. This is largely due to the high productivity and the fact that it is a highly technical crop, with very efficient irrigation and fertilization systems, and low requirements for pesticide treatments.

The relative cost of irrigation and fertilization has been increasing, but the high lemon yields make it very productive in relation to these inputs. The variety Fino is more productive than Verna and is more efficient in the use of resources such as water and fertilization, with a lower unit cost. On the other hand, the increasingly greater demands in relation to the appearance of the fruit have augmented the non-fresh marketable yield. These "waste: intended for industry" percentages penalize production in economic terms, increasing the cost of the lemon intended for fresh consumption. Additionally, it is necessary to emphasize the need for a unique and standardized methodology for LCC. It would lead to more complex analyses that would provide a deeper understanding of production processes and would enable the comparison of the LCC results of diverse products, in turn, market transparency would increase.

In environmental terms, the most impactful component is the production of inorganic fertilizers. A possible alternative is the transition to organic fertilization. The replacement of synthetic fertilizers with organic fertilizers could be total or partial, depending on how it affects costs and productivity. Irrigation is not a significant factor if the energy necessary to extract water at the source is not considered, but it becomes the main component of the impact categories when this is taken into account, especially if the proportion of desalinated water increases. Therefore, it is crucial that water management organizations provide detailed data that allow analysis to be carried out considering this variable with the aim of obtaining more precise results adjusted to reality. Furthermore, the more renewable energy the national mix uses, the lower the impact associated with irrigation will be. It has been proven here that emissions derived from the application of pesticides in the field are not a very relevant component of the environmental impact, regardless of the calculation methodology used. However, the existence of a clear, simple, and standardized methodology would be of interest, with the objective of unifying the results of the LCAs of agricultural products.

Lemon production in the SE of Spain has low values of GW, due to high productivity, low use of agricultural machinery, efficient fertilization adjusted to the needs of the crop, and climatic conditions that reduce (compared to other wetter areas) the quantity of pesticides applied and nitrous oxide emissions from the application of nitrogen fertilizers. Furthermore, farmers strictly comply with EU regulations on pesticides and, at the same time, biotechnological control is successfully applied more and more frequently.

To sum up, lemons grown in the conditions of the SE of Spain, in a conventional system with fertigation, and intended for the fresh market represent a sustainable product in economic and environmental terms.

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Appendix A

Table A1. Amortization of the investment of lemon Fino.

	Initial Investment for the Farm (EUR)	Initial Investment (EUR·ha^{-1})	Useful Life (Years)	Residual Value (EUR·ha^{-1})	Amortization (EUR·ha^{-1}·year $^{-1}$)	Fixed Costs * (EUR·ha^{-1}·year $^{-1}$)
Shed for equipment	16,000.0	1600.0	30.0	400.0	40.0	41
Preparation and planting	35,500.7	3550.1	25.0	0.0	142.0	144
Irrigation reservoir	33,717.5	3371.8	30.0	842.9	84.3	86
Irrigation equipment	13,125.0	1312.5	15.0	0.0	87.5	89
Irrigation network	18,972.9	1897.3	10.0	0.0	189.7	193
Various	1250.0	125.0	5.0	0.0	25.0	25
	118,566.1	**11,856.6**				**578**

The fixed cost of each concept expressed in EUR·ha^{-1}·year^{-1} includes the opportunity cost *.

Table A2. Amortization of the investment of lemon Verna.

	Initial Investment for the Farm (EUR)	Initial Investment (EUR·ha^{-1})	Useful Life (Years)	Residual Value (EUR·ha^{-1})	Amortization (EUR·ha^{-1}·year $^{-1}$)	Fixed Costs * (EUR·ha^{-1}·year $^{-1}$)
Shed for equipment	16,000.0	1600.0	30.0	400.0	40.0	41
Preparation and planting	37,215.0	3721.5	30.0	0.0	124.1	126
Irrigation reservoir	29,553.2	2955.3	30.0	738.8	73.9	75
Irrigation equipment	13,125.0	1312.5	15.0	0.0	87.5	89
Irrigation network	18,972.9	1897.3	10.0	0.0	189.7	193
Various	1250.0	125.0	5.0	0.0	25.0	25
	116,116.0	**11,611.6**				**549**

The fixed cost of each concept expressed in EUR·ha^{-1}·year^{-1} includes the opportunity cost *.

References

1. World Bank. *Global Economic Prospects*; The World Bank: Washington, DC, USA, 2023; ISBN 978-1-4648-1952-0.
2. United Nations Department of Economic and Social Affairs, Population Division. *World Population Prospects 2022: Summary of Results*; United Nations: New York, NY, USA, 2022; ISBN 978-92-1-001438-0.
3. United Nations Department of Economic and Social Affairs. *Global Sustainable Development Report 2023: Times of Crisis, Times of Change: Science for Accelerating Transformations to Sustainable Development*; United Nations: New York, NY, USA, 2023; ISBN 978-92-1-358511-5.
4. Beccali, M.; Cellura, M.; Iudicello, M.; Mistretta, M. Resource Consumption and Environmental Impacts of the Agrofood Sector: Life Cycle Assessment of Italian Citrus-Based Produdts. *Environ. Manag.* **2009**, *43*, 707–724. [CrossRef]
5. Beccali, M.; Cellura, M.; Iudicello, M.; Mistretta, M. Life Cycle Assessment of Italian Citrus-Based Products. Sensitivity Analysis and Improvement Scenarios. *J. Environ. Manag.* **2010**, *91*, 1415–1428. [CrossRef]
6. Falcone, G.; De Luca, A.; Stillitano, T.; Strano, A.; Romeo, G.; Gulisano, G. Assessment of Environmental and Economic Impacts of Vine-Growing Combining Life Cycle Assessment, Life Cycle Costing and Multicriterial Analysis. *Sustainability* **2016**, *8*, 793. [CrossRef]
7. European Comission. *A Farm to Fork Strategy*; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; European Commission: Brussels, Belgium, 2020.
8. European Environment Information and Observation. *Agriculture-Introduction*; European Environment Information and Observation (Eionet): Copenhagen, Denmark, 2020.
9. European Comission. *The European Green Deal. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*; European Commission: Brussels, Belgium, 2019.
10. European Comission. *EU Biodiversity Strategy for 2030*; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions; European Commission: Brussels, Belgium, 2020.
11. Maudos, J.; Salamanca, J. *Observatorio Sobre el Sector Agroalimentario Español en el Contexto Europeo: Informe 2022*; Cajamar Caja Rural: Almería, Spain, 2023; ISBN 978-84-95531-74-2.
12. CARM. *Estadística Agraria de Murcia 2020/21*; Comunidad Autónoma de la Región de Murcia; Consejería de Agua, Agricultura, Ganadería, Pesca, Medio Ambiente y Emergencias: Murcia, Spain, 2022.
13. Martin-Gorriz, B.; Gallego-Elvira, B.; Martínez Alvarez, V.; Maestre-Valero, J.F. Life Cycle Assessment of Fruit and Vegetable Production in the Region of Murcia (South-East Spain) and Evaluation of Impact Mitigation Practices. *J. Clean. Prod.* **2020**, *265*, 121856. [CrossRef]
14. *ISO 14040*; Environmental Management–Life Cycle Assessment: Principles and Framework. International Organization for Standards (ISO): Geneva, Switzerland, 2006.
15. *ISO 14044*; Environmental Management–Life Cycle Assessment: Requirements and Guidelines. International Organization for Standards (ISO): Geneva, Switzerland, 2006.
16. Clift, R.; Druckman, A. *Taking Stock of Industrial Ecology*; Springer Open: Cham, Switzerland, 2016; ISBN 978-3-319-20571-7.
17. Rivela, B.; Kuczenski, B.; Sucozhañay, D. Chapter 6. Life Cycle Sustainability Assessment-Based Tools. In *Assessing Progress Towards Sustainability*; Teodosiu, C., Fiore, S., Hospido, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 93–118. ISBN 978-0-323-85851-9.
18. Ciroth, A.; Huppes, G.; Klöpffer, W.; Rüdenauer, I.; Steen, B.; Swarr, T. *Environmental Life Cycle Costing*; Hunkeler, D., Lichtenvort, K., Rebitzer, G., Eds.; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: New York, NY, USA, 2008; ISBN 978-1-4200-5470-5.
19. Settanni, E.; Notarnicola, B.; Tassielli, G. Combining Life Cycle Assessment of Food Products with Economic Tools. In *Environmental Assessment and Management in the Food Industry*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 207–218. ISBN 978-1-84569-552-1.
20. *ISO 15663*; Petroleum, Petrochemical and Natural Gas Industries—Life Cycle Costing. International Organization for Standards (ISO): Geneva, Switzerland, 2021.
21. *ISO 15686*; Buildings and Constructed Assets -Service Life Planning—Life Cycle Costing. International Organization for Standards (ISO): Geneva, Switzerland, 2017.
22. Tamburini, E.; Pedrini, P.; Marchetti, M.; Fano, E.; Castaldelli, G. Life Cycle Based Evaluation of Environmental and Economic Impacts of Agricultural Productions in the Mediterranean Area. *Sustainability* **2015**, *7*, 2915–2935. [CrossRef]
23. Sottile, F.; Massaglia, S.; Peano, C. Ecological and Economic Indicators for the Evaluation of Almond (*Prunus dulcis* L.) Orchard Renewal in Sicily. *Agriculture* **2020**, *10*, 301. [CrossRef]
24. García Castellanos, B.; García Garcia, B.; García García, J. Evaluation of the Sustainability of Vineyards in Semi-Arid Climates: The Case of Southeastern Spain. *Agronomy* **2022**, *12*, 3213. [CrossRef]
25. Ribal, J.; Sanjuan, N.; Clemente, G.; Fenollosa, M.L. Medición de La Ecoeficiencia En Procesos Productivos En El Sector Agrario. Caso de Estudio Sobre Producción de Cítricos. *Econ. Agrar. Recur. Nat.* **2009**, *9*, 125–148.
26. Pergola, M.; D'Amico, M.; Celano, G.; Palese, A.M.; Scuderi, A.; Di Vita, G.; Pappalardo, G.; Inglese, P. Sustainability Evaluation of Sicily's Lemon and Orange Production: An Energy, Economic and Environmental Analysis. *J. Environ. Manag.* **2013**, *128*, 674–682. [CrossRef]

27. Cabot, M.I.; Lado, J.; Sanjuán, N. Multi-Season Environmental Life Cycle Assessment of Lemons: A Case Study in South Uruguay. *J. Environ. Manag.* **2023**, *326*, 116719. [CrossRef]
28. Canaj, K.; Mehmeti, A.; Cantore, V.; Todorović, M. LCA of Tomato Greenhouse Production Using Spatially Differentiated Life Cycle Impact Assessment Indicators: An Albanian Case Study. *Environ. Sci. Pollut. Res.* **2020**, *27*, 6960–6970. [CrossRef]
29. Roy, P.; Nei, D.; Orikasa, T.; Xu, Q.; Okadome, H.; Nakamura, N.; Shiina, T. A Review of Life Cycle Assessment (LCA) on Some Food Products. *J. Food Eng.* **2009**, *90*, 1–10. [CrossRef]
30. Cabot, M.I.; Lado, J.; Clemente, G.; Sanjuán, N. Towards Harmonised and Regionalised Life Cycle Assessment of Fruits: A Review on Citrus Fruit. *Sustain. Prod. Consum.* **2022**, *33*, 567–585. [CrossRef]
31. García García, J. *Análisis del Sector Del Limonero y Evaluación Económica de su Cultivo*; Consejería de Agricultura y Agua de la Región de Murcia: Murcia, Spain, 2014; ISBN 978-84-697-0909-2.
32. Sgroi, F.; Candela, M.; Di Trapani, A.M.; Foderà, M.; Squatrito, R.; Testa, R.; Tudisca, S. Economic and Financial Comparison between Organic and Conventional Farming in Sicilian Lemon Orchards. *Sustainability* **2015**, *7*, 947–961. [CrossRef]
33. Raschio, G.; Smetana, S.; Contreras, C.; Heinz, V.; Mathys, A. Spatio-Temporal Differentiation of Life Cycle Assessment Results for Average Perennial Crop Farm: A Case Study of Peruvian Cocoa Progression and Deforestation Issues. *J. Ind. Ecol.* **2017**, *22*, 1378–1388.
34. Brandão, M.; Heijungs, R.; Cowie, A.L. On Quantifying Sources of Uncertainty in the Carbon Footprint of Biofuels: Crop/Feedstock, LCA Modelling Approach, Land-Use Change, and GHG Metrics. *Biofuel Res. J.* **2022**, *9*, 1608–1616. [CrossRef]
35. Arcas Lario, N.; Alcón Provencio, F. Contribución de Las Entidades de "Economía Social" a La Gestión Eficiente Del Agua Para Uso Agrícola: Situación En La Región de Murcia. *Rev. Estud. Coop.* **2007**, *91*, 7–33.
36. Soto García, M.; Martínez Álvarez, V.; Martín Górriz, B. *El Regadío en la Región de Murcia. Caracterización y Análisis Mediante Indicadores de Gestión*; Sindicato Central de Regantes del Acueducto Tajo-Segura: Murcia, Spain, 2014; ISBN 978-84-697-0372-4.
37. Grindlay Moreno, A.L.G.; Lizágarra Mollinedo, C.L. Regadío y territorio en la Región de Murcia: Evolución y perspectivas de futuro. *Estud. Territ.* **2012**, *44*, 281–298.
38. Ben Abdallah, S.; Gallego-Elvira, B.; Imbernón-Mulero, A.; Martínez-Alvarez, V.; Maestre-Valero, J. Environmental Footprint of Organic and Conventional Grapefruit Production Irrigated with Desalinated Seawater in Spain. *Sustain. Prod. Consum.* **2023**, *39*, 326–335. [CrossRef]
39. Porras Castillo, I. Técnicas de cultivo para la mejora de la calidad en limonero. *Vida Rural* **2005**, *210*, 24–28.
40. García Lidón, Á.; del Río Conesa, J.A.; Porras Castillo, I.; Fuster Soler, M.D.; Ortuño Tomás, A. *El Limón y sus Componentes Bioactivos*; Técnica y de Estudios; Consejería de Agricultura, Agua y Medio Ambiente: Murcia, Spain, 2003; ISBN 84-688-2698-7.
41. Porras Castillo, I. Nuevas tendencias en el cultivo el limonero. *Agricultura* **2007**, *895*, 285–293.
42. Generalitat Valenciana. *Patrones y Variedades de Cítricos*; Generalitat Valenciana Consellería de Agricultura, Pesca y Alimentación: Valencia, Spain, 2001; ISBN V-1324-2001.
43. Porras Castillo, I.; Pérez Tornero, O. La colección de limonero del IMIDA. *Investig. IMIDA* **2007**, *1*, 46–51.
44. Soria Alfonso, A. *La Fertirrigación del Limonero*; Formación Agroalimentaria; Comunidad Autónoma de la Región de Murcia Consejería de Agricultura y Agua: Murcia, Spain, 2008; ISBN MU-1.004-2008.
45. Ballestero, E. *Economía de la Empresa Agraria y Alimentaria*; Mundi-Prensa: Madrid, Spain, 2000; ISBN 978-84-7114-863-6.
46. Mitrović, I.; Todorović, M.; Marković, M.; Mehmeti, A. Eco-Efficiency Analysis of Rainfed and Irrigated Maize Systems in Bosnia and Herzegovina. *J. Water Clim. Chang.* **2023**, *14*, 4489–4505. [CrossRef]
47. Samuelson, P.A.; Nordhaus, W.D. *Economía*; McGraw-Hill Interamericana: Madrid, Spain, 2006; ISBN 978-84-481-5154-6.
48. Ministerio de Medio Ambiente y Medio Rural y Marino. *Guía Práctica de la Fertilización Racional de los Cultivos en España*; Ministerio de Medio Ambiente y Medio Rural y Marino (MAGRAMA): Madrid, Spain, 2010; ISBN 978-84-491-0997-3.
49. Lucas Espadas, A. *Plagas y Enfermedades de Limón y Pomelo en la Región de Murcia*; Formación agroalimentaria; Comunidad Autónoma de la Región de Murcia Consejería de Agricultura y Agua: Murcia, Spain, 2008; ISBN MU-981-2008.
50. Yan, M.; Cheng, K.; Yue, Q.; Yan, Y.; Rees, R.M.; Pan, G. Farm and Product Carbon Footprints of China's Fruit Production—Life Cycle Inventory of Representative Orchards of Five Major Fruits. *Environ. Sci. Pollut. Res.* **2016**, *23*, 4681–4691. [CrossRef]
51. Ribal, J.; Ramírez-Sanz, C.; Estruch, V.; Clemente, G.; Sanjuán, N. Organic versus Conventional Citrus. Impact Assessment and Variability Analysis in the Comunitat Valenciana (Spain). *Int. J. Life Cycle Assess.* **2016**, *22*, 571–586. [CrossRef]
52. Ingrao, C.; Matarazzo, A.; Tricase, C.; Clasadonte, M.T.; Huisingh, D. Life Cycle Assessment for Highlighting Environmental Hotspots in Sicilian Peach Production Systems. *J. Clean. Prod.* **2015**, *92*, 109–120. [CrossRef]
53. Bartzas, G.; Vamvuka, D.; Komnitsas, K. Comparative Life Cycle Assessment of Pistachio, Almond and Apple Production. *Inf. Process. Agric.* **2017**, *4*, 188–198. [CrossRef]
54. Rapa, M.; Ciano, S. A Review on Life Cycle Assessment of the Olive Oil Production. *Sustainability* **2022**, *14*, 654. [CrossRef]
55. European Environment Agency. *EMEP/EEA Air Pollution Emission Inventory Guidebook 2019. Technical Guidance to Prepare National Emission Inventories*; EEA Report; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-9213-806-6.
56. The Intergovernmental Panel on Climate Change. *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC: Geneva, Switzerland, 2019; ISBN 978-4-88788-232-4.
57. Gazulla, C.; Raugei, M.; Fullana-i-Palmer, P. Taking a Life Cycle Look at Crianza Wine Production in Spain: Where Are the Bottlenecks? *Int. J. Life Cycle Assess.* **2010**, *15*, 330–337. [CrossRef]

58. Bosco, S.; Di Bene, C.; Galli, M.; Remorini, D.; Massai, R.; Bonari, E. Greenhouse Gas Emissions in the Agricultural Phase of Wine Production in the Maremma Rural District in Tuscany, Italy. *Ital. J. Agron.* **2011**, *6*, 93–100. [CrossRef]
59. Villanueva-Rey, P.; Vázquez-Rowe, I.; Moreira, M.T.; Feijoo, G. Comparative Life Cycle Assessment in the Wine Sector: Biodynamic vs. Conventional Viticulture Activities in NW Spain. *J. Clean. Prod.* **2014**, *65*, 330–341. [CrossRef]
60. De Luca, A.I.; Falcone, G.; Iofrida, N.; Stillitano, T.; Strano, A.; Gulisano, G. Life Cycle Methodologies to Improve Agri-Food Systems Sustainability. *Riv. Studi Sulla Sostenibilita* **2015**, *1*, 135–150. [CrossRef]
61. Ferrara, C.; De Feo, G. Life Cycle Assessment Application to the Wine Sector: A Critical Review. *Sustainability* **2018**, *10*, 395. [CrossRef]
62. Martín-Górriz, B.; Martínez-Alvarez, V.; Maestre-Valero, J.F.; Gallego-Elvira, B. Influence of the Water Source on the Carbon Footprint of Irrigated Agriculture: A Regional Study in South-Eastern Spain. *Agronomy* **2021**, *11*, 351. [CrossRef]
63. Machin Ferrero, L.M.; Wheeler, J.; Mele, F.D. Life Cycle Assessment of the Argentine Lemon and Its Derivatives in a Circular Economy Context. *Sustain. Prod. Consum.* **2022**, *29*, 672–684. [CrossRef]
64. García García, J.; García García, B. Sustainability Assessment of Greenhouse Pepper Production Scenarios in Southeastern Spain. *Agronomy* **2022**, *12*, 1254. [CrossRef]
65. Nemecek, T.; Antón, A.; Basset-Mens, C.; Gentil-Sergent, C.; Renaud-Gentié, C.; Melero, C.; Naviaux, P.; Peña, N.; Roux, P.; Fantke, P. Operationalising Emission and Toxicity Modelling of Pesticides in LCA: The OLCA-Pest Project Contribution. *Int. J. Life Cycle Assess.* **2022**, *27*, 527–542. [CrossRef]
66. European Commission. *COMMISSION RECOMMENDATION (EU) 2021/2279 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations*; European Commission: Brussels, Belgium, 2021.
67. García García, J. *Estructura de Costes de las Orientaciones Productivas Agrícolas de la Región de Murcia: Frutales de Hueso y Cítricos*; Técnica; Consejería de Agua, Agricultura, Ganadería y Pesca de la Región de Murcia: Murcia, Spain, 2018; ISBN MU-198-2018.
68. Fernandez Zamudio, M.Á. *Metodología-IVIA: Determinación Costes de Cultivo. Resultados Preliminares de Costes de Mandarino, Naranjo y Caqui*; IVIA: Valencia, Spain, 2022.
69. García García, J. *Estructura de Costes de las Orientaciones Productivas Agrícolas de la Región de Murcia: Frutos Secos, Frutales de Pepita, Vid y Olivo*; Técnica; Consejería de Agua, Agricultura, Ganadería y Pesca de la Región de Murcia: Murcia, Spain, 2019; ISBN MU 422-2019.
70. Bessou, C.; Basset-Mens, C.; Tran, T. LCA Applied to Perennial Cropping Systems: A Review Focused on the Farm Stage. *Int. J. Life Cycle Assess.* **2013**, *18*, 340–361. [CrossRef]
71. Sanjuan, N.; Úbeda, L.; Clemente, G.; Mulet, A. LCA of Integrated Orange Production in the Comunidad Valenciana (Spain). *Int. J. Agric. Resour. Gov. Ecol.* **2005**, *4*, 163–177.
72. Cerutti, A.K.; Beccaro, G.L.; Bruun, S.; Bosco, S.; Donno, D.; Notarnicola, B.; Bounous, G. Life Cycle Assessment Application in the Fruit Sector: State of the Art and Recommendations for Environmental Declarations of Fruit Products. *J. Clean. Prod.* **2014**, *73*, 125–135. [CrossRef]
73. Aguilera, E.; Guzmán, G.; Alonso, A. Greenhouse Gas Emissions from Conventional and Organic Cropping Systems in Spain. I. Herbaceous Crops. *Agron. Sustain. Dev.* **2015**, *35*, 713–724. [CrossRef]
74. Lo Giudice, A.; Mbohwa, C.; Clasadonte, M.T.; Ingrao, C. Environmental Assessment of the Citrus Fruit Production in Sicily Using LCA. *Ital. J. Food Sci.* **2013**, *25*, 202–212.