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Can Precise Irrigation Support the Sustainability of Protected Cultivation? A Life-Cycle Assessment and Life-Cycle Cost Analysis

Kledja Canaj [1] , **Angelo Parente** [2], **Massimiliano D'Imperio** [2] , **Francesca Boari** [2], **Vito Buono** [3],
Michele Toriello [3] , **Andi Mehmeti** [4,*] **and Francesco Fabiano Montesano** [2,*]

1. Department of Management, Finance and Technology, LUM Giuseppe Degennaro University, S.S. 100, Km 18, 70010 Casamassima, Italy; canaj.phdstudent@lum.it
2. Institute of Sciences of Food Production, National Research Council (CNR-ISPA), Via Amendola, 122/O, 70126 Bari, Italy; angelo.parente@ispa.cnr.it (A.P.); massimiliano.dimperio@ispa.cnr.it (M.D.); francesca.boari@ispa.cnr.it (F.B.)
3. Sysman Progetti & Servizi S.r.l, Via A. Montagna 2, Zona PIP, 72023 Mesagne, Italy; buono.vito@gmail.com (V.B.); toriello@sys-man.it (M.T.)
4. International Center for Advanced Mediterranean Agronomic Studies (CIHEAM-Bari), Via Ceglie 9, 70010 Valenzano, Italy
* Correspondence: mehmeti@iamb.it (A.M.); francesco.montesano@ispa.cnr.it (F.F.M.)

Abstract: To address sustainability challenges, agricultural advances in Mediterranean horticultural systems will necessitate a paradigmatic shift toward smart technologies, the impacts of which from a life cycle perspective have to be explored. Using life cycle thinking approaches, this study evaluated the synergistic environmental and economic performance of precise irrigation in greenhouse Zucchini production following a cradle-to-farm gate perspective. A cloud-based decision support system and a sensor-based irrigation management system (both referred to as "smart irrigation" approaches) were analyzed and compared to the farmer's experience-based irrigation. The potential environmental indicators were quantified using life cycle assessment (LCA) with the ReCiPe 2016 method. For the economic analysis, life cycle costing (LCC) was applied, accounting not only for private product costs but also for so-called "hidden" or "external" environmental costs by monetizing LCA results. Smart irrigation practices exhibited similar performance, consuming on average 38.2% less irrigation water and energy, thus generating environmental benefits ranging from 0.17% to 62%. Single score results indicated that life cycle environmental benefits are up to 13% per ton of product. The cost-benefit analysis results showed that even though the implementation of smart irrigation imposes upfront investment costs, these costs are offset by the benefits to water and energy conservation associated with these practices. The reduction of investment costs and higher water costs in future, and lower internal rate of return can further enhance the profitability of smart irrigation strategies. The overall results of this study highlight that smart and innovative irrigation practices can enhance water-energy efficiency, gaining an economic advantage while also reducing the environmental burdens of greenhouse cultivation in a Mediterranean context.

Keywords: LCA; LCC; smart farming; precision irrigation; sustainability

1. Introduction

As the world requires more food to meet the demands of population growth, greenhouse crop production (often referred to as controlled environment agriculture) is becoming the backbone of intensive agriculture both in developed economies and in new emerging markets. It is becoming increasingly important in the Mediterranean region to increase crop productivity and profit potential while also supplying food on an all-year-round basis while bolstering food security [1]. Greenhouse horticulture is recognized globally for its ability to higher productivity, earlier harvesting, more consistent production, and higher quality [2,3],

but environmental impacts remain a controversial issue and challenging issue that cannot be ignored [4]. Greenhouse production is one of the most intensive agricultural systems, often characterized by heavy use of energy, water, and chemical inputs [3,5]. Intensive farming practices create environmental issues of different kinds, including eutrophication, toxicity, and water footprint [6].

With growing pressure on already scarce agricultural resources, the greenhouse industry is compelled to make more efficient use of resources and more sustainable farming practices by adopting cultivation practices and new technologies [7]. In recent years, smart farming through computer-based decision support systems [8] and sensor-based technologies [9] has allowed better control of fertilization and irrigation and higher efficiency of resource utilization (water, fertilizers, etc.) as well as prevention of soil-borne diseases [2]. Yet, benefits are under controversy in some instances due to higher water efficiency and high energy use for water supply, which increases total consumption on a basin scale [10]. In addition to increasing efficiency, precision agriculture also alters the economics of agricultural production since the initial investment costs for new technologies required are high [11]. When incorrectly applied, smart farming technologies can cause losses arising from investments made by farmers, thus decreasing the economic water productivity index and the overall sustainability [12].

Smart farming has associated co-benefits and trade-offs, necessitating a systemic approach to explore interconnectedness. Recently, the sustainability of cropping practices has focused on nexus thinking and lifecycle-based indicators to capture the complex and often "hidden" linkages between water consumption, energy, and the environment [13]. Life cycle assessment (LCA) thinking has been applied to analyze variable rate irrigation and nutrient applications in grape pear orchards [14], paddy rice [15], olives [16], and irrigation schemes [17]. Bacenetti [15] demonstrated that a variable-rate fertilization strategy combined with remote sensing products could lead to a reduction in environmental impact greater than 10%. Fotia et al. [16] demonstrated that precise irrigation by DSS-based management can reduce by 5.3 to 18% the overall environmental impact per 1 ton of olives, or 10.4 to 22.6% per 1 ha of cultivated land. Balafoutis et al. [18] demonstrated that variable rate application of water in a vineyard can reduce GHG emissions by 8.8%. These benefits were up 28.3% when combined with the variable rate application of nutrients. El Chami et al. [19] conducted a cost-benefit assessment of precision irrigation with variable rate technique versus conventional irrigation, calculating a 23.0% lower global warming potential for precision irrigation. Along with environmental impacts, the performance analysis of precision farming needs to consider economic aspects to study the actual economic benefits that technologies bring to the farm (the savings and revenues) and determine if it is profitable or not. According to studies [17,20], smart farming technologies can produce positive economic results in comparison to conventional practices, however, this is site-specific. Jobbágy et al. [21] estimated that precision irrigation can reduce the water cost in potato production in Slovakia by 27%, or 9.1 EUR/ha. It has been demonstrated by Belayneh et al. [22] that sensor-based set-point irrigation has an annual net savings of $5263 to $138,408 over a range of water prices in a commercial nursery operation. Lichtenberg et al. [23] estimated that annual profit was 156% higher under the wireless sensor-based irrigation than under the nursery's standard practices in Gardenia production.

One of the objectives of the IR2MA project (an international cooperation project between Italy and Greece under the Interreg EU program, https://www.interregir2ma.eu/ accessed on 12 December 2021) was to test soil moisture sensors and decision support systems approaches for irrigation and nutrient management in vegetable production in Southern Italy. In this region, the available water sources are primarily used for agriculture, and it has become ever more difficult to meet the water demand, with far-reaching sustainability implications for the crop industry. Precision agriculture is a market opportunity. However, there is a need to produce evidence of the actual impact of precision agriculture technologies on environmental sustainability and economic performance [20].

In this study, LCA and life cycle costing (LCC) were used to explore the environmental impacts and economic implications of water-efficient irrigation. A commercial cloud-based DSS (Bluleaf™) and an innovative sensor-based automatic irrigation management system were tested in greenhouse Zucchini (*Cucurbita pepo* L.) production, analyzed and compared to conventional irrigation management based on the farmer's perception of crop needs. The aim of this paper is twofold. First, the results of this study provide a reference study on the multiple environmental impacts of zucchini using state-of-art life cycle impact assessment methods. Very few studies deal with the LCA of other greenhouse crops such as zucchini [24,25]. In recent years, there has been a significant increase in the production and consumption of zucchini in Italy. The country is the second-largest producer in the EU (with 37.1% of total production). As a result, we believe that a specific case study on Zucchini will be of interest to Italian and international stakeholders, as demand for lifecycle-based information and sustainably produced agricultural products is increasing [26]. Secondly, we answer: what are the effects of the proposed water-related innovations on environmental performance and profitability? There is a general lack of scientific publications directly linking smart farming to sustainability impacts [27].

2. Materials and Methods

2.1. Production System and Experimental Setup

This research was based on data collected during a greenhouse zucchini (cultivar 'Velvia', Syngenta) cultivation cycle (95 days, from transplant to the final harvest) in the period September–December 2019. The test was carried out in a 1700 m^2 plastic unheated greenhouse in the agricultural company "Azienda Agricola Carrillo Nicola", located in the countryside of Ascoli Satriano (FG, southern Italy, 41°23′ N, 15°60′ E). The area is considered a major region for vegetable crop production.

The irrigation empiric management normally adopted by the company, based on the farmer's experience (hereafter referred to as "farmer-led"), was compared with two "smart" approaches for automatic irrigation scheduling (Figure 1): one based on the real-time soil moisture measurements performed by a wireless sensor network installed in the greenhouse, with automatic activation of the irrigation intervention when a certain pre-defined critical moisture set-point based on the hydrological characteristics of the soil was reached (hereafter referred to as "sensor-based"); another based on the calculation of the evapotranspiration performed by a commercial DSS, the BluLeaf® system (www.bluleaf.it, accessed on 12 December 2021), developed in its prototype form as part of a previous collaboration between CNR-ISPA and Sysman Progetti e Servizi Srl (hereafter referred to as "cloud-based DSS"). A layout of the field experimental setup is reported in Figure 1.

A prototype system (the Greenhouse Irrigation Control Kit, GICK2), designed and implemented by CNR-ISPA in collaboration with Sysman Progetti e Servizi Srl in the framework of the IR2MA project, was installed in the greenhouse facility to carry out irrigation in treatments based on the two smart strategies described above. In brief, the system acquires data from wireless sensor networks, which feeds a decision algorithm that, in turn, automates the irrigation of the crop, resulting in on-demand irrigation. Using the system's connection to the cloud, the operator can monitor the trends of the parameters of interest and set and modify the irrigation strategy accordingly. The actuation section allows the automatic management of devices (pumps, solenoid valves, etc.) for the execution of the irrigation intervention.
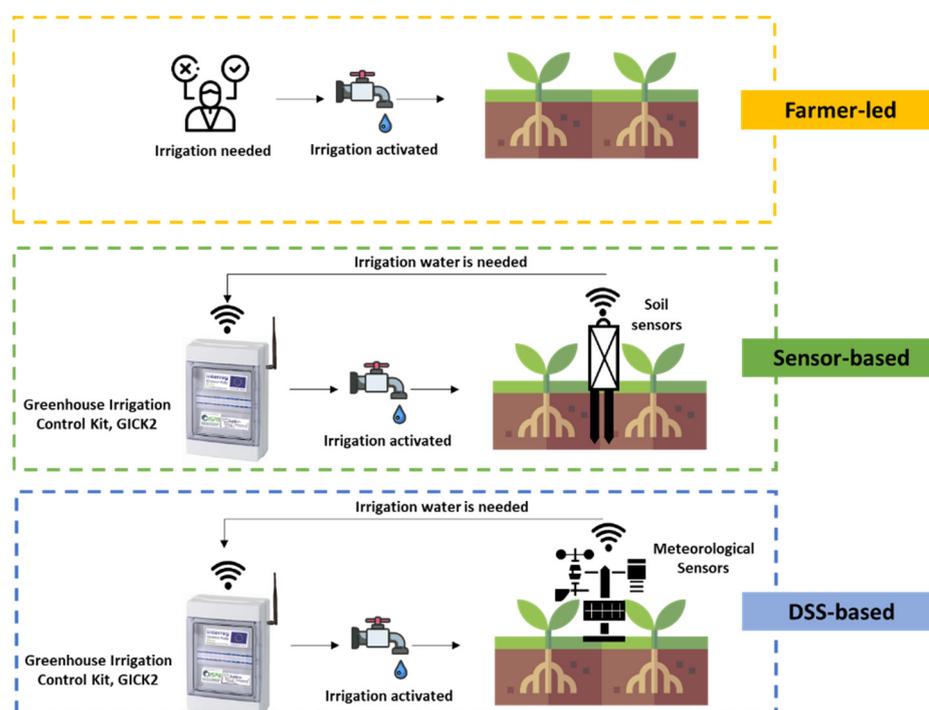
Figure 1. The layout of irrigation strategies compared for ucchini cultivation.

The GICK2 was interfaced with: (i) a wireless network of sensors for soil moisture real-time measurements (SMT100, TRUEBNER GmbH, Germany), positioned at several points of the sensor-based irrigation treatment plot at two soil depths (25 and 40 cm); and (ii) the BluLeaf® system with the related micro-meteorological sensors functional to the calculation of evapotranspiration for the automatic irrigation management in the cloud-based DSS treatment plot.

For this study, the GICK2 has been programmed to activate two distinct solenoid valves serving the two distinct crop plots (of approximately 70 m² each) based on the two "smart" irrigation strategies described above, respectively. A third plot was also identified in the greenhouse for collecting data representative of crop performance under the farmer's empiric irrigation management.

All plants in the greenhouse were subjected to standard cultivation practices commonly adopted by the grower, including fertilization, soil tillage, weed control, plant disease control, with the only exception of irrigation management in the two smart irrigation plots as described above. Irrigation took place with micro-irrigation and water extracted from local artesian wells to a depth of 36 m. Water pumps are fed by an electric pump. Fertilizer was applied in the irrigation water. Farm mechanization activities were done using a 74 kW tractor (100 HP).

2.2. Calculation Framework and Tools

The analysis of environmental and economic impacts was conducted with life cycle assessment (LCA) and life cycle costing (LCC). Figure 2 shows a schematic of the main components of the life cycle impact analysis. We conducted both LCA and LCC based on a functional unit of 1-tonne zucchini using a cradle-to-farm gate perspective (Figure 3). Production and delivery of chemicals (fertilizers and pesticides), production and delivery of energy sources (electricity and diesel), and water were included. Primary input data was collected from a field investigation, as described in Section 2.1. The data is representative of a Mediterranean context. Field emissions regarding water emissions, soil direct and indirect dinitrogen monoxide, ammonia volatilization, nitrate leaching, and nitrous oxide were computed following LCA guidelines [28,29]. The management of the greenhouse

facility (construction, maintenance, and disposal of pavilions or tunnels) was not included in the analysis.
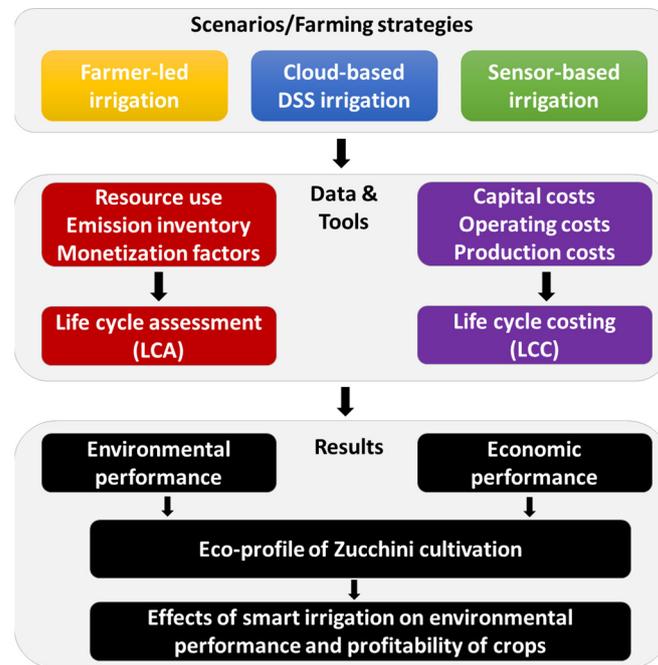
Figure 2. Framework for life cycle assessment (LCA) and life cycle costing analysis (LCC) of zucchini production.
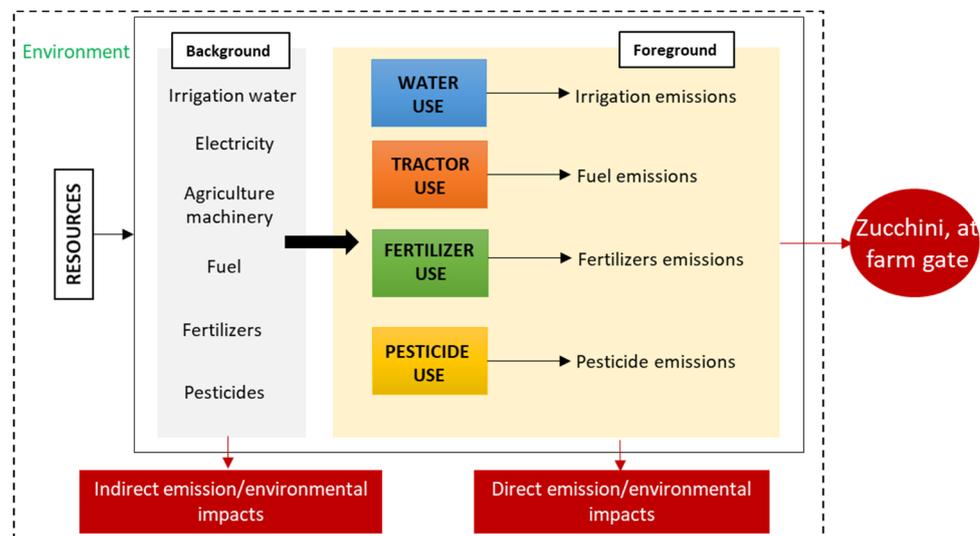
Figure 3. System boundaries for a cradle-to-farm-gate life cycle analysis for zucchini production.

The impact assessment was conducted using the OpenLCA software v.1.10.3 [30] and the ReCiPe 2016 (H) methodology [31]. The OpenLCA software was chosen for the project based on the authors' prior experience and ease of accessibility. The ReCiPe 2016 life cycle impact model was chosen because it provides insightful information on a broad set of environmental impact categories and audiences. The analysis included eighteen midpoint indicators and three endpoint indicators (Figure 4). Global warming, freshwater, and marine eutrophication, terrestrial acidification, ozone formation, stratospheric ozone depletion, ionizing, radiation, water consumption, particulate matter formation, and land use are among the midpoint indicators. The three aggregated endpoint impact categories were damage to human health, ecosystems, and resources. Along with them, we use

weighting factors to facilitate the establishment of an overall indicator of environmental impact. The single-figure scores assist the non-LCA expert in understanding the relative environmental performance of each strategy analyzed. The final impact was produced by using an average weighting set (Europe H/A, recommended): 400 human health, 400 ecosystem quality, and 200 resources. It means that the impact indicator value is multiplied by the weighting factor to obtain the single score value. The database Ecoinvent version 3.1 [32], the most consistent and transparent life cycle inventory database, was used for life cycle inventory datasets of background processes (production of fertilizer, pesticides, electricity, and diesel).
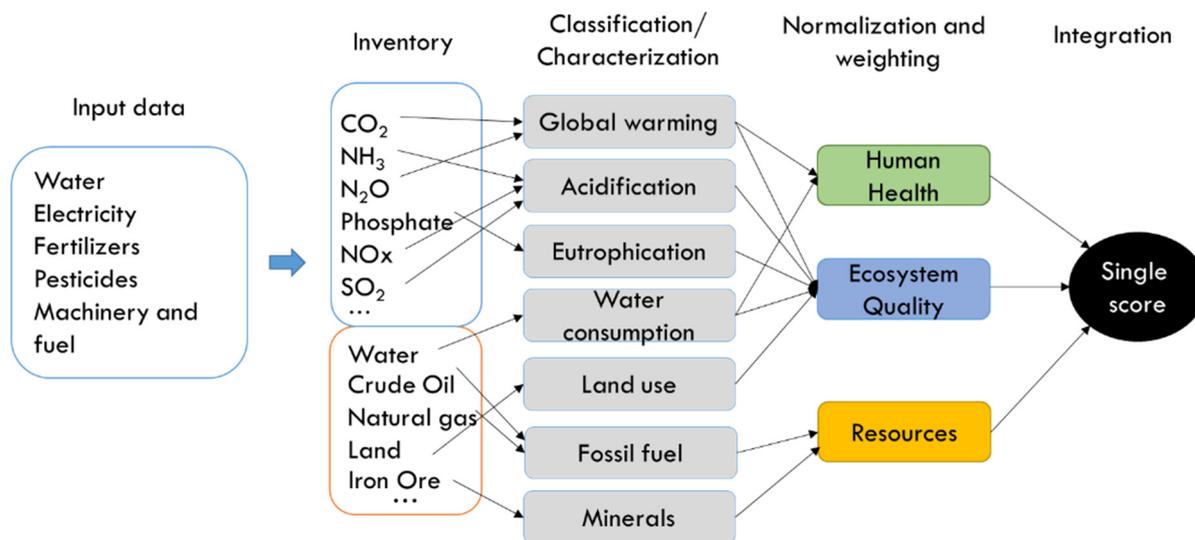
Figure 4. ReCiPe 2016 impact pathway from inventory to aggregation to a single score.

The economic appraisal compared the economic costs and benefits of smart irrigation. As the logical counterpart of LCA, life cycle costing (LCC) was used to assess the cost implications. The life cycle cost model accounted for internal (production costs) using LCC and external (environmental) costs following economic valuation or monetization of LCA results (Table 1).

Table 1. Classification of life cycle cost components.

LCC Cost	LCC Component	LCC Sub-Component
Internal	Cost of raw materials used in crop production	Water, energy, fertilizers, pesticides, machinery, investment, etc.
External	Cost of various environmental effects	Water consumption, toxicity, Acidification (grams of SO_2, NO_X, and NH_3), eutrophication (grams of NO_X and NH_3), land use (m^2/year), or other measurable impacts

The consideration of external costs is one way of addressing trade-offs between environmental dimensions with purely economic ones. The ReCiPe 2016 was monetized using LCA-based conversion factors used previously by Canaj et al. [33]. The net present value of costs for DSS and sensor were calculated over a 5-year lifetime considering an internal rate of return of about 10%. Initial investment costs of the DSS and sensor-based systems were 3000 and 3500 EUR/ha, respectively. Table 2 present the data used in the economic analysis.

Table 2. Input data used in cost analysis.

Input	Amount	Unit
Irrigation Water	0.4	€/m^3
Electricity	0.12	€/kWh
Urea	0.39	€/kg
Ammonium sulphate	0.26	€/kg
Calcium nitrate	0.37	€/kg
Phosphorus fertilizer	0.27	€/kg
Potassium fertilizer	0.55	€/kg
Diesel Fuel	0.85	€/kg
Machinery	15	€/hour
Lubricating Oil	5	€/liter
Investment cost DSS irrigation	3000	€/ha
Investment cost sensor-based	3500	€/ha

3. Results

3.1. Life Cycle Inventory (LCI)

Table 3 describes the input-output data for zucchini cultivation. In general, similar results were observed for the two strategies applied for rational irrigation (DSS-based and sensor-based), while a significant difference was found between those and the farmer's experience-based irrigation management in terms of water usage. Water use is differentiated by the amount of water withdrawn and water consumed. It can be seen that the total water requirement could be reduced from more than 3500 m^3/ha in the farmer's irrigation strategy to 2160 m^3/ha when the sensor-based automatic management was used. Therefore, a total water saving of 1340 m^3/ha or 38.3% was obtained. This translates to an average savings of 340 kWh/ha. In terms of water consumed (Water consumption: water removed from, but not returned to the same drainage basin. Water consumption can be because of evaporation, transpiration, product integration, or release into a different drainage basin or the sea. Evaporation from reservoirs is considered water consumption), the difference between a farmer's irrigation strategy and rational irrigation is only 70.84 m^3/ha or 3.5%. Water consumption is the amount that does not return, not even as waste. In sensor-based irrigation management, the frequency of irrigation is adjusted automatically, leading to the majority of the water supply being consumed (evaporated or incorporated into the product). On the other hand, under farmer management, a large amount of water is returned to the environment and is available for reuse. It should be noted that, despite the significant water savings obtained in the two smart approaches compared to the empiric irrigation management normally adopted on the farm, no significant differences were observed in terms of crop yield, with an average of 30.5 tons/ha in all management strategies.

3.2. Impact on Environmental Peformance

Calculated environmental life cycle impact indicators are presented in Table 4. The results show that the implementation of smart farming technologies enhanced the environmental performance in the majority of the impact categories. Specifically, the environmental burdens are decreased by 0.03% to almost 62%. Specifically, ozone depletion, ionizing radiation, and marine eutrophication in freshwater show better environmental performance after the implementation of smart irrigation. Ozone depletion and ionizing radiation were linked to a reduction in electricity use, while marine eutrophication was linked to a reduction in nutrient leaching. There was no discernible difference in the amount of water consumed.

Table 3. Input-output data for 1 ha of zucchini greenhouse production.

Parameter	Unit	Farmer-Led Irrigation	Cloud-Based DSS Irrigation	Sensor-Based Irrigation
Seeds	kg/ha	320	320	320
Crop Yield	ton/ha	30.5	30.5	30.5
Gross irrigation supply	m^3/ha	3500	2174	2160
Water consumption	m^3/ha	2021.8	1956.6	1944
Energy consumption	kWh/ha	1120	696	691.1
Total N-fertilizer	kg N/ha	135	135	135
Urea	kg N/ha	200	200	200
Ammonium sulfate	kg N/ha	100	100	100
Calcium nitrate	kg N/ha	140	140	140
P-fertilizer	kg P_2O_5/ha	80	80	80
K-fertilizer	kg K_2O/ha	100	100	100
Ammonia	kg NH_3/ha	16.35	16.35	16.35
Dinitrogen monoxide	kg N_2O/ha	5.13	5.13	5.13
Nitrogen oxides	kg NO_X/ha	0.93	0.93	0.93
Nitrates	kg NO_3/ha	177.6	59.21	59.21

Table 4. Environmental impacts attributed to 1-ton zucchini product using farmer experience and soil-moisture irrigation-based management.

Name	Unit	Farmer Irrigation	Cloud-Based DSS Irrigation	Sensor-Based Irrigation
		Midpoint		
Fine particulate matter formation	kg $PM_{2.5}$ eq	10.45	10.43	10.42
Fossil resource scarcity	kg oil eq	36.24	32.66	32.62
Freshwater ecotoxicity	kg 1,4-DCB	83.07	82.96	82.91
Freshwater eutrophication	kg P eq	0.02	0.01708	0.01706
Global warming	kg CO_2 eq	785.62	770.46	770.45
Human carcinogenic toxicity	kg 1,4-DCB	2.13	1.965	1.963
Human non—carcinogenic toxicity	kg 1,4-DCB	40.82	38.187	38.183
Ionizing radiation	kBq Co-60 eq	7.66	5.693	5.685
Land use	m2a crop eq	214.41	214.35	214.21
Marine ecotoxicity	kg 1,4-DCB	2.28	2.063	2.06
Marine eutrophication	kg N eq	0.46	0.1763	0.1761
Mineral resource scarcity	kg Cu eq	0.60	0.5992	0.5985
Ozone formation, Human health	kg NOx eq	0.55	0.53	0.5285
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.04	0.985	0.983
Stratospheric ozone depletion	kg CFC11 eq	0.0021	0.001972	0.00197
Terrestrial acidification	kg SO_2 eq	1.43	1.373	1.37
Terrestrial ecotoxicity	kg 1,4-DCB	150.76	140.28	140.28
Water consumption	m^3	375.42	373.18	372.77
		Endpoint		
Human Health	DALY	1.49×10^{-3}	1.302×10^{-3}	1.299×10^{-3}
Ecosystems	species.yr	6.71×10^{-6}	5.705×10^{-6}	5.69×10^{-6}
Resources	USD2013	10.25	9.103	9.09

Less energy-related emissions and resource consumption from smart farming will decrease environmental pollution and contribute to lower human health damage, better ecosystem quality, and higher resource availability. The current assessment results show that the health damage can be reduced by 12%, the damage to ecosystem quality by 15%, and the damage to resources by 11%.

Figure 5 presents LCA results as a single score. The total environmental impact in points (Pt) was equal to 28.82 points/ton, 25.15 points/ton, and 25.1 points/ton, re-

spectively. This means a reduction of about 13% per ton of Zucchini when using smart irrigation strategies.
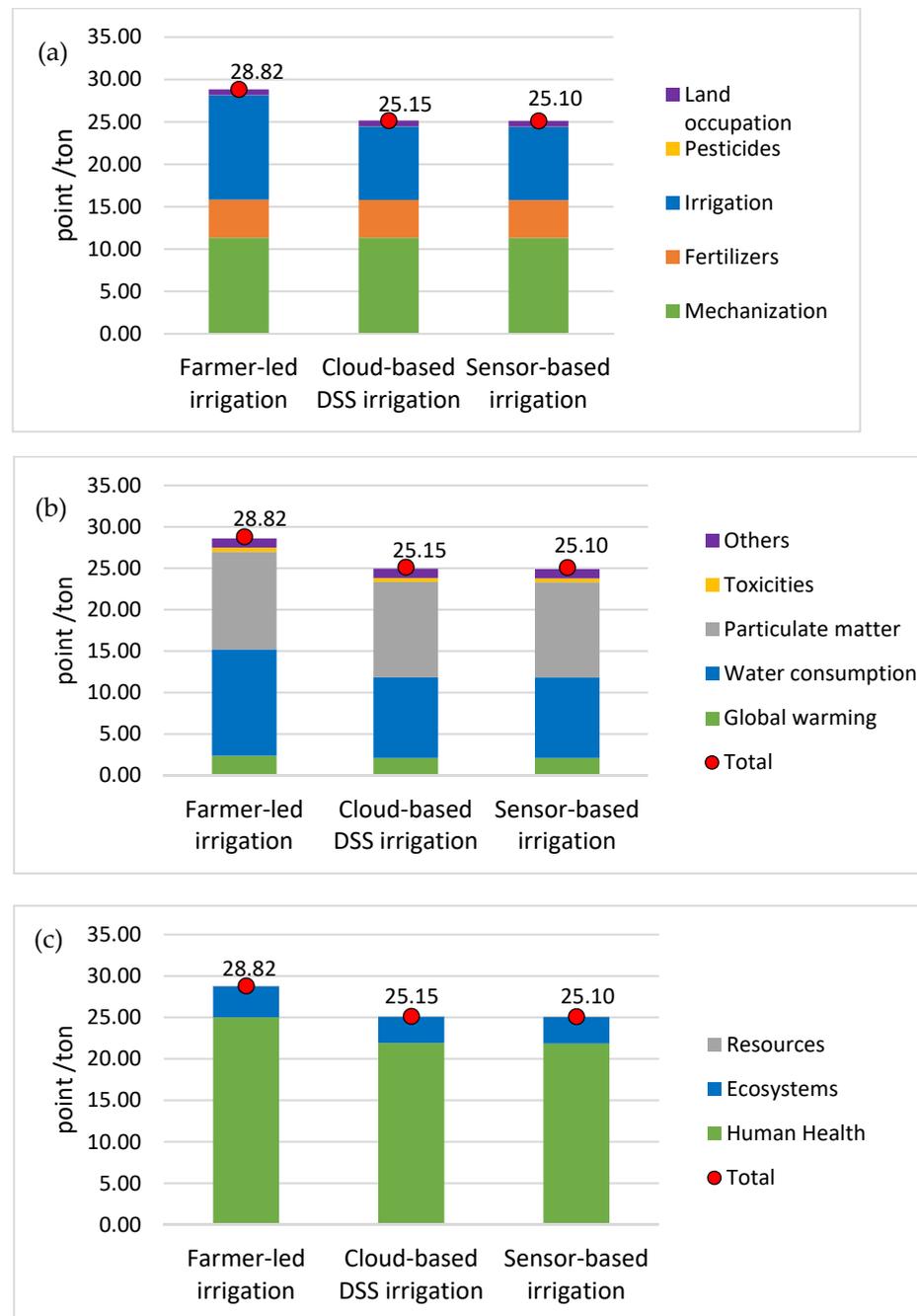
Figure 5. Environmental impact (ReCiPe single score) of Zucchini production under different management strategies showing contribution analysis of (**a**) processes, (**b**) midpoint impact categories, and (**c**) endpoint indicators.

Looking at the process's environmental single score results (Figure 5a), irrigation shares 35% to 42% of total environmental impacts. The main drivers of impacts (Figure 5b) are fine particulate matter formation (41 to 46%), water consumption (38 to 43%), and global warming (8.3 to 8.53%). These impacts are primarily driven by fertilizer production and emissions, followed by water and electricity consumption for irrigation. For damage impacts (Figure 5c), human health contributes most to the environmental single score, sharing more than 85% of the impacts. The results of LCA are consistent with previous studies

highlighting that precision agriculture can have a positive impact on the environmental performance of crop cultivation.

3.3. Impact on Economic Indicators

Figure 6 presents the direct production costs per 1 hectare of zucchini cultivation. The results are broken down by the different processes to facilitate the identification of the main contributors. The total cost of irrigation per hectare was 3274 EUR for farmer irrigation, 3147 EUR for DSS-based irrigation, and 3222 EUR for sensor-based irrigation systems (Figure 6). The costs per ton of product were 107.3 EUR, 103.2 EUR, and 105.7 EUR, respectively. The annualized cost benefits of precision irrigation via DSS and sensor-based were 127 EUR/ha (4%) and 105.7 EUR/ha (+1.6%), respectively. As is apparent from Figure 6, the water cost was the major cost component. The capital cost contribution is relatively small. They constitute 16% and 18% of total private production costs for cloud-based DSS and sensor-based management, respectively.
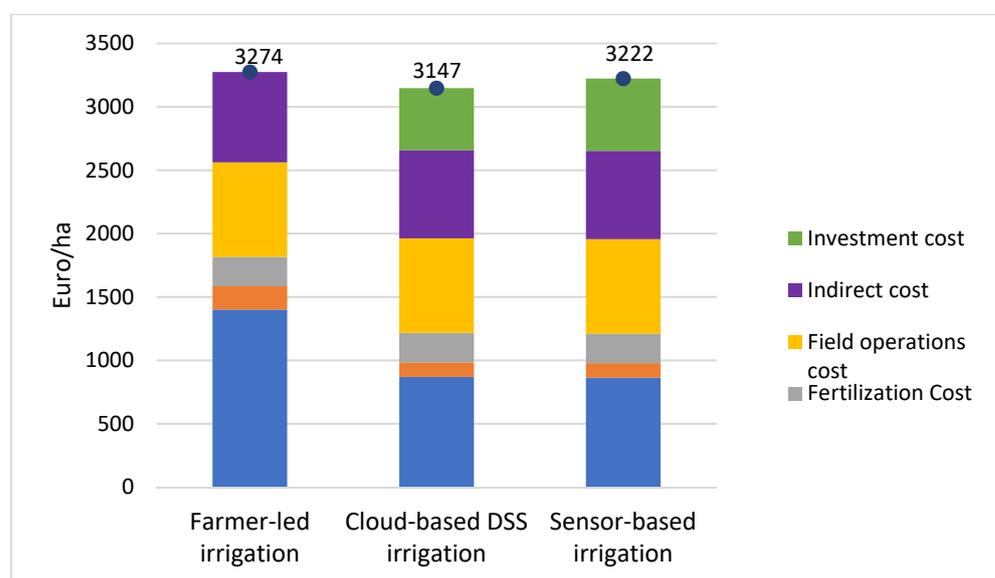
Figure 6. Life cycle cost of zucchini cultivation under different irrigation management strategies.

We further compared the external environmental cost and combined it with the internal cost to produce a total cost profile, i.e., a final synthetic economic–environmental indicator expressed in monetary terms (Figure 7).

For the calculation of external costs, the environmental impact indicators presented in Table 3 were used. The total cost (the sum of the internal and external costs) was 431.4 EUR/ton for the farmer-led irrigation, 422.2 EUR/ton for the cloud-based DSS, and 424.3 EUR/ton for the sensor-based irrigation. The overall benefits in this study were 9.14 EUR/ton for the cloud-based DSS and 7.1 EUR/ton for sensor-based irrigation. The life cycle external environmental costs were estimated at 324 EUR/ton for the farmer-led irrigation, 319 EUR/ton for the cloud-based DSS, and 318.6 EUR/ton for the sensor-based irrigation. For smart irrigation strategies, we see a similar pattern since LCA performance was similar. Of the external costs, fertilizer is the predominant contributor. Hence, the limited benefits in terms of external environmental costs are because major LCA impacts are controlled by fertilization, which is the same among the three production systems. The results show that the external cost can be almost double the internal cost, while the economic benefits associated with the internal cost were found to be of higher relevance than external costs. There is no general agreement on external costs and their share of the total cost. Canaj et al. [23] demonstrated that the external cost of crop production could range from 23–57% of the total cost. Olba-Zięty et al. [34] demonstrated that the external cost of poplar chip production was 20% of the total cost, while Baaqel et al. [35] that the

total monetized cost of production accounting for externalities was more than double of the direct costs. Overall, our findings confirm the hypothesis that precision agriculture have generally a positive impact on farm productivity and economics [20]. The sensitivity analysis (Table 5) shows that the reduction of investment costs, higher water costs, and lower internal rate of return can enhance the profitability of smart irrigation strategies.
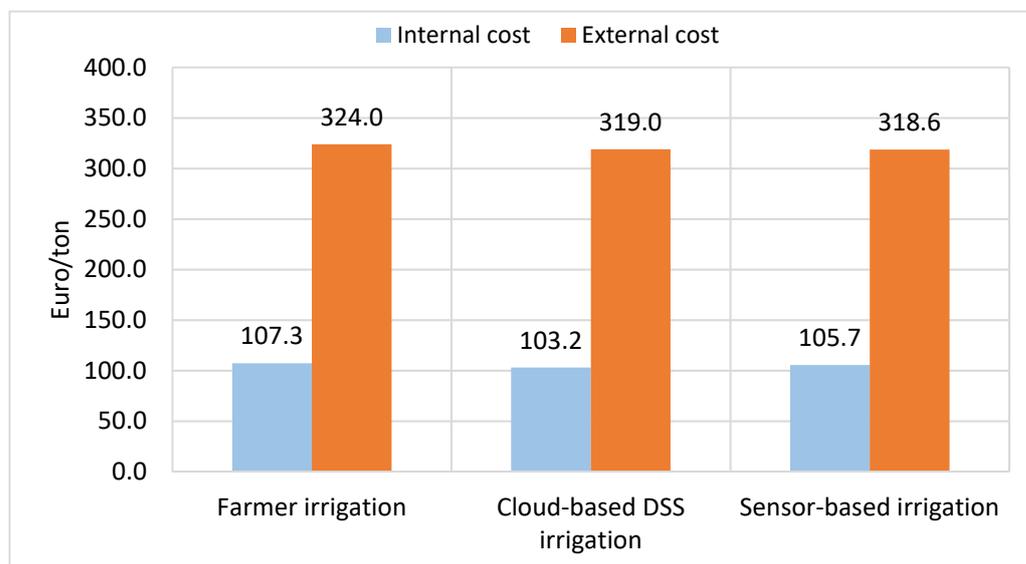
Figure 7. Total costs of irrigation management on zucchini cultivation including external environmental costs following the monetization of LCA results.

Table 5. Effect of different parameters on life cycle cost (LCC) of Zucchini production per 1 ton of product.

Scenario	Farmer-Led Irrigation	Cloud-Based DSS Irrigation	Sensor-Based Irrigation
Baseline	107.3 (431.3)	103.2 (422.2)	105.7 (424.3)
Water Cost = 0.6 EUR/m^3	130.9 (450)	117.8 (436.8)	120.2 (438.8)
Internal rate of return = 5%	107.3 (431.3)	99.9 (418.9)	101.8 (420.4)
Internal rate of return = 15%	107.3 (431.3)	106.7 (425.7)	109.8 (428.4)
Investment cost = +20%	107.3 (431.3)	106.4 (425.4)	109.4 (428)
Investment cost = −20%	107.3 (431.3)	100 (419)	101.9 (420.5)

4. Discussion and Conclusions

Improving food production and consumption systems is central to any discussion of sustainable development from both an environmental and socio-economic standpoint [36]. This path requires life cycle thinking, measurement, and management strategies toward sustainable solutions and eco-innovation [37]. Two common ways to apply a life cycle perspective include life cycle assessment (LCA) and life cycle costing (LCC). While LCA focuses primarily on burdens linked to emissions into the environment and resources, LCC aims at assessing cost along the supply chain [38]. A broad variety of published life cycle thinking studies of food products has emerged in recent years. However, the use of these tools for supporting the impact assessment of smart farming technologies and practices in greenhouse production is still relatively limited. Consequently, stakeholders are increasingly interested in knowing the economic and environmental cost-benefits of

the proposed agricultural innovations. This study combined LCA-LCC analysis to assess the environmental and economic performance of irrigation management in greenhouse horticulture systems in a Mediterranean context. The multi-indicator analysis permitted us to generate an extended view of environmental impacts, thus limiting the shifting of the targeted environmental problems. Moreover, single score analysis helped not only to arrive at an overall conclusion about the economic and environmental potential but also highlighted benefits and drawbacks in an intuitively understandable way, especially to non-LCA experts (i.e., company managers, farmers, and the general public) and decision-makers with limited or no sustainability background. Our findings indicate that more sustainable greenhouse crop production systems can be achieved via decision support-based and sensor-controlled irrigation due to savings in terms of inputs distributed in the field. There is a clear benefit of smart irrigation in terms of water and energy use, bringing co-benefits to the economy and the environment. The findings confirmed the conclusions made in the previous publications, claiming that the use of different smart farming technologies guarantees sustainable agriculture from an environmental [15,39] and economic [21–23] point of view.

The current study emphasizes the importance of incorporating life cycle thinking into crop production systems. Using a framework that includes LCA and LCC, it is possible to identify the activities that have the greatest impact, better assess the implications of products, and enhance decision-making in favor of sustainability. Future research studies can examine the impact of shorter production times, the combined effect of smart irrigation and fertilization, the addition of social LCA indices and indicators, or any combination of these factors. Lastly, future work should investigate the impacts of protected crops using similar multi-criteria model/s to explore differences among characterization models.

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