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Environmental and Agro-Economic Sustainability of Olive Orchards Irrigated with Reclaimed Water under Deficit Irrigation

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Abstract: Increasing the economic and environmental sustainability of irrigated agriculture is a vital challenge for the Mediterranean crop production sector. This study explores the effects of the adoption of reclaimed water (RW) as source of irrigation in conjunction with the application of deficit irrigation strategies in an olive orchard (different genotypes) located within the "Valle dei Margi" farmhouse (Eastern Sicily). Specifically, the RW was obtained in situ by treating the wastewater coming from the farmhouse throughout a nature-based treatment wetland system (TW). The effects of RW on crop water status (CWS) was assessed by conducting plant-based measurements (i.e., leaf water potential, Ψ; and leaves' relative water content, RWC) and determining satellite-based biophysical indicators. An economic and environmental evaluation of the proposed sustainable irrigation practices was carried out using the life cycle assessment (LCA) approach. The RW quality showed high variability due to fluctuations in the number of customers at the farmhouse during the COVID-19 pandemic period. A strong impact on the variation in Ψ was observed among the olive orchard under the different water regimes, evidencing how CWS performances are conditioned by the genotype. However, no differences in leaves' RWC and in satellite-based biophysical indicators were detected. Finally, the results of the LCA analysis underlined how the use of RW may permit us to obtain important economic and environmental gains, representing an added value for olive growing for operating in accordance to more sustainable development models.

Keywords: constructed wetland; physiological indicators; sustainable management practices; water-saving strategies; wastewater treatment

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1. Introduction

The olive is a typical Mediterranean cultivation that significantly contributes to the economy of the agro-industrial sector. In Italy, olive cultivation is typically carried out under the dry conditions of the southern regions of the peninsula (e.g., Apulia, Basilicata and Sicily), except for table olive production, which takes advantage of the irrigation [1]. As a consequence of the climate change, a greater water demand is expected for the olive groves even in nontraditional seasons [2]. In this context, even if the olive is a fairly drought-tolerant species, it is practical to envision that, in the near future, its cultivation may no longer be sustainable for some Italian areas [3]. In light of these environmental and economic considerations, the Italian "National Olive Oil Plan" aims to strengthen olive production, without increasing the already strong pressure on natural resources. In this sense, to face the scarce water availability and water quality deterioration that characterize the Mediterranean water resources, the adoption of sustainable irrigation practices becomes pivotal for improving the water use efficiency (WUE) of the overall olive cultivation.

Nowadays, several water-saving measures are applied to increase the environmental sustainability of typical Mediterranean crops, including citrus [4,5], almond [6] and vineyard groves [7]. Most of the available water-saving measures represent the result of several years of technological development in the irrigation industry sector (e.g., drip irrigation, ultra-low drip irrigation and micro-sprinkler), together with the recent advances of knowledge related to the implementation of deficit irrigation (DI) criteria (e.g., partial root-zone drying (PRD), regulated deficit irrigation (RDI), sustained deficit irrigation (SDI); [8]). At the base of the positive application of the DI criteria, the use of soil–plant–atmosphere (SPA) continuum monitoring techniques is always recommended. In particular, plant-based indicators (e.g., stem water potential; leaf water potential, Ψ; and stomatal conductance) are commonly used for determining the crop water status (CWS). In addition, the adoption of spatially distributed information, acquired by an unmanned aerial vehicle (UAV) or satellite, permits us to derive biophysical indicators (e.g., vegetation indexes) recognized as proxies for the CWS for the entire field [9].

Under the water-saving scenario, the supplementary use of reclaimed water (RW) for irrigation purposes represents an emergent practice for further increasing the WUE of olive cultivations (refer to the references in Supplementary Materials Table S1) and reducing the associated water footprint [10,11]. Generally, the results of the studies summarized in Supplementary Table S1 conclude that (i) RW can be applied as an additional water resource for olive irrigation in water-scarce Mediterranean environments; (ii) the RW-related effects on olive trees and olive oil need to be quantified both in physiological and qualitative terms, respectively; and (iii) different olive cultivars respond differently to RW use.

Currently, even if the adoption of alternative sources for irrigation is paramount for increasing the limited water resources' availability, especially in arid and semiarid agricultural regions, the reuse of treated wastewater (WW) is made difficult by the limits deriving from the reference legislations [12]. The perspective of reusing RW for the irrigation of olive trees may have great practical benefits, even if some environmental matters associated with this practice nowadays represent an open discussion [13,14]. Furthermore, only a few studies have deepened the analysis of the effects of agricultural practices (e.g., limited to the use of olive growing systems and/or the use of irrigation) on the environmental sustainability of olive tree cultivation [11,15–18]. In this regard, Arborea et al [19] underlined the importance of conducting case-by-case analyses to quantify the cost-effectiveness of using RW in local scenarios.

In light of the state-of-the-art, the main objective of the study was to determine the effects of the adoption of sustainable irrigation strategies in an olive grove, with particular reference to the integrated use of DI and the use of RW. In particular, this study had the following specific objectives: (i) to evaluate the efficiency of a constructed treatment wetland (TW) system to produce RW suitable for the irrigation reuse, (ii) to identify the olive CWS resulting from the adoption of DI and RW reuse strategies and (iii) to study the economic viability of the proposed water management practices for the olive grove under study.

2. Materials and Methods

2.1. Study Site and Treatments Description

A two-years study (2020–21) was conducted in an olive orchard located at the "Valle dei Margi" farmhouse in Sicily, Insular Italy (Grammichele, Catania province (CT); WGS84 N 37.25, E 14.60). The climate of the study area is semi-arid Mediterranean, with average annual air temperature (T_{air}), rainfall and reference evapotranspiration (ET_0) values of 17 °C, 683 mm and 1101 mm, respectively (Figure 1). Climatic data were registered for the period 2012–2021 by the agrometeorological station of Caltagirone (CT), managed by Servizio Informativo Agrometeorologico Siciliano (SIAS); the station is located 3 km away from the olive orchard. During the irrigation seasons under study, the average cumulative

ET_0 and rainfall were 335 and 25 mm, respectively (June–September period of both 2020 and 2021).

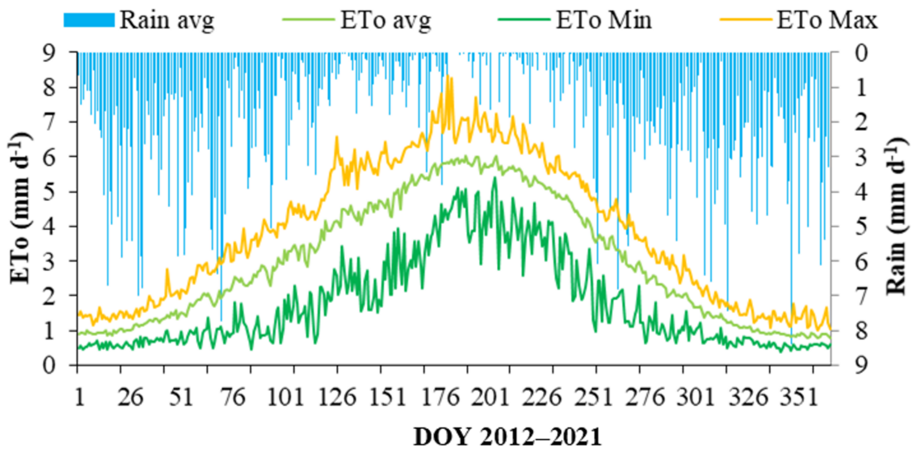

Figure 1. Average, minimum and maximum daily trend of the reference evapotranspiration (ET_0) and precipitation (mm d^{-1}) for the period 2012–2021 at the Caltagirone SIAS station.

The olive grove (*Olea europaea* L.) consisted of 10-year-old trees, belonging to 4 cultivars widely cultivated in Sicily, i.e., "Nocellara Etnea", "Carolea", "Moresca" and "San Benedettese". The grove was divided into homogeneous groups of about 20 trees for each variety, with a total of 96 trees. The main characteristics of the olive orchard are reported in Table 1.

Table 1. Main characteristics of the olive orchard under study.

Parameter	Value	Units
Surface	3456.0	m^2
Canopy diameter	2.8	m
Canopy area	6.7	m^2
Area of the tree planting layout	36.0	m^2
Distance among the trees	6.0	m
Trees number	96.0	-
Canopy ground cover	18.6	%

During the study period, the orchard was supplied with both fresh water (FW) and RW. An automated drip irrigation system was designed and used for irrigation volumes' distribution. The system was divided into 2 independent irrigation sectors (i.e., FW and RW), where the following irrigation treatments were applied and compared:

i. Control treatment (T1), which received an irrigation volume corresponding to 100% of the crop water requirements (ET_c), using surface drip lines consisting of 4 emitters per tree, with a flow rate of 7.9 L h^{-1} each, at 1 bar, and a total discharge of 31.6 L h^{-1} per tree;
ii. DI treatment (T2), supplied with 80% of ET_c, alternatively on the two sides of the root system, using the PRD strategy, on weekly basis. PRD involved the use of 2 separate surface drip lines consisting of 4 emitters, with a flow rate of 4.0 and 2.1 L h^{-1} (at 1 bar), respectively, and a total discharge of 24.4 L h^{-1} per tree;
iii. DI treatment (T3), where a constant reduction of 50% of the irrigation volume was applied using surface drip lines consisting of 4 emitters, with a flow rate of 4.0 L h^{-1} (at 1 bar) per tree and a total discharge of 16 L h^{-1} per tree.

The irrigation volume was applied 3 times a week, early in the morning. The water deficit was applied at T2 and T3 since the beginning of the irrigation season (from DOY (day-of-year) 185 to 244 in 2020 and from DOY 172 to 258 in 2021) during the pit-hardening period, which is considered to be the most drought-resistant period for olive trees [20,21]. During the irrigation season in 2020, due to the reduced production of WW from the farmhouse, as a consequence of the emergency caused by the COVID-19 pandemic, the irrigation sectors were both supplied with FW.

In order to characterize the textural and hydraulic variability of the soil at the study site, 36 soil samples were collected and used for laboratory determinations, including soil apparent density, (ρ_a, g cm^{-3}), soil water content (cm^3 cm^{-3}) at the field capacity (FC, at 0.2–0.3 bar) and wilting point (WP, at 15 bar), respectively. The overall results of the soil's physical and hydraulic characterization show a sandy loam texture, with average (and standard deviation) ρ_a, FC and WP values equal to 1.50 (±0.13) g cm^{-3}, 0.34 (±0.05) and 0.12 (± 0.03) cm^3 cm^{-3}, respectively (Table 2).

Table 2. Average and standard deviation (in brackets) values of the main physical and hydraulic characteristics of the soil at the irrigation treatments (T1, T2 and T3) under FW and RW, which refer to fresh water and reclaimed water, respectively; ρ_a, FC and WP indicate the soil apparent density (g cm^{-3}), the soil water content (cm^3 cm^{-3}) at the field capacity (FC) and the wilting point (WP).

Irrigation Water	Irrigation Treatment	ρ_a (g cm^{-3})		FC (cm^3 cm^{-3})		WP (cm^3 cm^{-3})	
FW	T1	1.59	(0.07)	0.31	(0.07)	0.11	(0.04)
	T2	1.30	(0.10)	0.36	(0.04)	0.15	(0.03)
	T3	1.56	(0.06)	0.33	(0.06)	0.12	(0.03)
RW	T1	1.53	(0.14)	0.34	(0.02)	0.11	(0.02)
	T2	1.51	(0.14)	0.31	(0.05)	0.11	(0.03)
	T3	1.51	(0.07)	0.37	(0.01)	0.14	(0.01)

2.1.1. Treatment Wetland System and Removal Efficiency

FW and RW were used as the source for irrigation of the olive orchard during the irrigation season 2021 (June–September). In particular, RW was derived from a TW system located at the study area and used as secondary treatment for WW coming from the farmhouse activities (30 m^{3}d^{-1}). WW was preliminary treated by a degreaser and an Imhoff tank (Figure 2). The TW system consists of 2 treatment units in series: (i) a horizontal subsurface flow (H-SSF) bed and (ii) a free water surface flow (FWS) unit.

The H-SSF unit has a surface area of about 350 m^2 and it is filled, for an average depth of about 0.60 m, with volcanic gravel (grain diameter, ϕ: 8–12 mm), and with coarser volcanic gravel (ϕ = 80–100 mm) at its initial and terminal sections. The role of H-SSF unit is to reduce the organic matter (biochemical oxygen demand, BOD; and chemical oxygen demand, COD) and the total suspended solids (TSS) from the WW. The H-SSF bed is planted with several ornamental macrophytes species (*Cyperus papyrus* var. *Siculus*, *Cyperus alternifolius*, *Typha latifolia*, *Carex schoenoplectus* and *Iris pseudacorus*), with a density of 3–5 plants m^{-2}. The FWS unit has a surface area of about 180 m^2 and an average water depth of about 0.70 m, and its banks are planted with *Phragmites australis*, which is highly tolerant to pollutants.

The FW and the incoming WW/outgoing RW (from each single stage of the TW system) were sampled (24 to 42 samples for period) within 2 reference periods (i.e., Period I, September 2019–September 2020; and Period II, October 2020–September 2021). The analyses of the samples were conducted in a laboratory, according to the methods of [22], to determine the following chemical–physical and microbiological parameters: pH (-); electrical conductivity (EC, µS cm^{-1}), TSS (mg L^{-1}), BOD_5 (mg L^{-1}), COD (mg L^{-1}), orthophosphates (P-PO_4, mg L^{-1}), ammonia nitrogen (N-NH_3, mg L^{-1}), nitrous nitrogen (N-NO_2, mg L^{-1}), nitric nitrogen (N-NO_3, mg L^{-1}), organic nitrogen (N_{org}, mg L^{-1}), total nitrogen (N_{tot}, mg L^{-1}) and *Escherichia coli* (CFU 100 mL^{-1}).

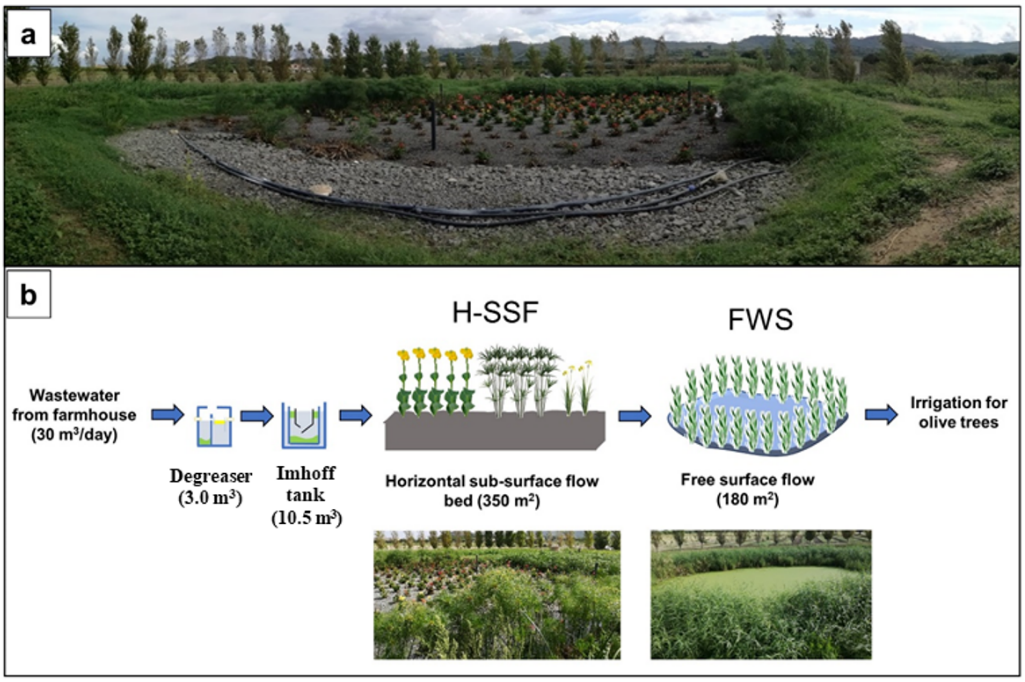

Figure 2. Overview of the treatment wetland (TW) system at the "Valle dei Margi" farmhouse in Sicily (**a**) and treatment units (**b**).

An assessment of the removal efficiency (RE, %) for each chemical–physical parameter and a $\log_{10}$ reduction in CFUs for *E. coli* were performed in accordance with the methods reported in [23]. The analytical results of the characterization were compared with the limits imposed by the Italian National legislation for discharging into surface water bodies [24] and to those issued by the Ministry of Environment and Ministry of Agriculture, Ministry of Public Health, for technical measures for the reuse of WW [25].

2.1.2. Scheduling Irrigation Volumes

The irrigation volumes for the olive orchard were based on the estimation of the ET_c through the single crop coefficient (K_c) (FAO-56 approach, [26]). In particular, ET_c was obtained by calculating, on a climatic basis, the ET_0 and using the K_c for the phenological stage of the olive trees under study (Equation (1)):

$$ET_c = ET_0 \times K_c \quad (1)$$

where ET_0 is expressed in mm d^{-1}, and K_c values refer to the olive trees, as reported in the FAO-56 manual [26] and adjusted according to [27] (i.e., average value of 0.49 during June–September). Data for ET_0 calculation were obtained from the Caltagirone SIAS station in the reference period 2012–2021 (as reported in Figure 1).

The net irrigation requirement (IR, mm d^{-1}) of the olive orchard was determined using a simplified water balance performed on a monthly scale (2012–21), by subtracting the rainfall contributions from the monthly values of the ET_c. For the determination of the irrigation dose (ID, mm d^{-1}), the following equation was implemented:

$$ID = IR \times K_r \times (1/K_a) \times (1/K_d) \quad (2)$$

where K_r (i.e., 0.38) takes into account the percentage of shading by the canopy (18.6%, Table 1) on the planting layout (i.e., 36 m^2; Table 1) [28]; and K_a (i.e., 0.90) and K_d (i.e., 0.95) depend on the design characteristics of the drip irrigation system, referring to the irrigation efficiency and the emission uniformity, respectively.

The performances of the irrigation system were evaluated by monitoring the supplied irrigation volumes with volumetric water meters at the beginning and at the end of each irrigation phase. In addition, emission uniformity tests (EU tests, %; [29]) were carried out in the field by measuring the flow rate from 64 sampling emitters.

2.2. Crop Water Status Evaluation

The CWS of the olive trees subjected to the different water treatments was monitored using both ground- and satellite-based methods. The details on the used methodological approaches are described in the following subsections.

2.2.1. Ground-Based Physiological Monitoring

The Ψ (MPa) was monitored fortnightly during the irrigation seasons of 2020–21, using a Scholander pressure chamber (Model 600, PMS Instrument Company, Albany, OR, USA), at the maximum stressed period of the day (11:00–14:00, local time). The Ψ survey consisted of the removal of a shoot apex on a vegetative branch with a sharp blade, which was inserted into the chamber and pressurized with inert gas (nitrogen) until a drop of xylem sap was emitted from the cutting surface of the petiole. The Ψ value is significant because it indicates the potential for the leaf to retain water. The measurements were carried out on two leaves per tree on 3 trees per treatment.

Five leaves from each tree per cultivar were collected at the end of the trial of both years. Leaves were weighted to obtain the fresh weight (F_W) and then dried (D_W) in an oven for 48 h at 80 °C in order to determine the leaves' relative water content (RWC), which is expressed as the percentage of weight after the complete dehydration and obtained with the following equation [30]:

$$RWC = 100 \times (F_W - D_W)/F_W \quad (3)$$

Note that the leaves' RWC is recognized as a reliable indicator of plant hydration status under conditions of drought and high T_{air} [31].

2.2.2. Satellite-Based Biophysical Indices

A satellite approach was applied to determine the spatial distribution of the main reflective features of the olive trees and, thus, identify, by analyzing their temporal variations, possible effects related to the application of the sustainable irrigation practices under study (e.g., DI under RW). In particular, for the irrigation seasons of 2020–21, a total of six multispectral images (level 2A), acquired under clear-sky conditions by the sensors on board the Sentinel-2 satellites (2A/2B), were analyzed. These high-spatial-resolution images (i.e., 10 m and 20 m for the visible/near infrared (VNIR) and short-wave infrared (SWIR) portions of the electromagnetic spectrum, respectively) are freely distributed by the European Spatial Agency (ESA) through the Copernicus platform. The satellite information was processed for the definition of the main biophysical indices, i.e., albedo [32], normalized vegetation index (NDVI, [33]) and leaf area index (LAI, [34]), using the "Graph Builder" and "Batch processor" toolboxes implemented in SNAP software (v.8.0.0, ESA©). In more detail, the NDVI maps were calculated using the tool "Biophysical Processor", which combines the spectral information of the red (B4) and near-infrared (NIR, B8) bands. The LAI calculation was determined by implementing the neural algorithm proposed by [34]. This approach is based on the spectral information referring both to the VNIR and SWIR portions of the electromagnetic spectrum (i.e., B3-B7, B8a, B11 and B12). The albedo was obtained according to [32]. The values of the obtained biophysical indices (albedo, NDVI and LAI) were extracted for each image at the scale of the entire olive grove and at the treatment level, and their main statistical features (average, standard deviation and standard error values) were calculated with reference to the periods of June, July and August in 2020–21. Three additional Sentinel-2 images from 2019, i.e., before the application of the sustainable irrigation practices, were acquired and processed in order to be used as a reference. An analysis of variance (ANOVA) was conducted on the biophysical indices to identify the main effects of the treatments under study over the reference period. Tukey's test was applied to assess the differences, with a significance level (*p*-value) of 0.05 (Statistix v.9.0, Analytical Software, USA).

2.3. Qualitative Characteristics of the Olive Oil

The oil samples (2 replicas for treatment) underwent transesterification at room temperature as follows: 20 mg of oil was weighed and placed in 8 mL glass vials in which 600 µL of hexane and 60 µL of methanolic solution of KOH 2N were added. The mixture was vigorously stirred for 2 min, and then the sample was incubated for a further 2 h. When the phases were well separated, the upper part (the hexane fraction containing the fatty acid methyl esters) was treated with anhydrous Na_2SO_4 to eliminate the water residues, then filtered (0.45 µm pore size, 25 mm diameter, GVS Filter Technology) and injected into a GC-FID and GC-MS for analysis.

Gas chromatographic (GC) analyses were run on a Shimadzu gas chromatograph, Model 17-A, equipped with a flame ionization detector (FID), and with the operating software Class VP Chromatography Data System version 4.3 (Shimadzu). The SPB-5 capillary column (15 m × 0.10 mm × 0.10 µm) was used, and helium was used as the carrier gas (0.9 mL/min). Injection in split mode (1:200), injected volume of 1 µL (4% essential oil/CH2Cl2 v/v), and injector and detector temperature of 250 and 280 °C, respectively. Linear velocity in column 45 mL/L. The oven temperature was held at 80 °C for 1 min, and then it was increased in increments of 10 degrees, up to 280 °C. Percentages of compounds were determined from their peak areas in the GC-FID profiles. Gas chromatography–mass spectrometry (GC-MS) was carried out in the fast mode on a Shimadzu GC-MS mod. GCMS-QP5050A, with the same column and the same operative conditions used for GC-FID, operating software GCMS solution version 1.02 (Shimadzu). Ionization voltage of 70 eV, electron multiplier of 900 V, and ion source temperature of 180 °C. Mass spectra data were acquired in the scan mode in m/z range 40–400. The same oil solutions (1 µL) were injected with the split mode (1:96). The components were identified based on their GC retention index.

2.4. Evaluation of the Economic and Environmental Sustainability of the Olive Orchard

To assess the environmental and economic sustainability performances of the olive orchard under the different olive-growing management systems (i.e., DI strategies with FW and RW, respectively), primary data were identified and collected in an inventory. Specifically, these primary data were acquired by performing direct interviews with the olive grower, who provided technical–agronomic data (such as the cultivated area, planting pattern, cultivar, age of plants, productivity per hectare, soil type and slope) and information on the olive amounts needed for oil production, the amount of olive oil produced and the list of the agronomic management operations carried out at the olive orchard (including type and number of cultivation operations, irrigation, pest control and fertilization, period and duration of interventions, machinery characteristics and energy consumption). The interviews were conducted after informed consent was given by the interviewees in accordance with the Regulation (EU) 2016/679 on the protection of natural persons in regard to the processing of personal data and the free movement of such data.

The proposed methodological approach, in support of the economic–business choices, was carried out at two different operational levels: (i) to study the economic impacts through the analysis of the farm incomes of the conduction models under examination [35–37] and (ii) to analyze the environmental impacts through life cycle assessment (LCA) methodology [17,38–40].

The collected dataset was monetized considering current market prices to determine the economic values of the various olive-growing management system scenarios. In this sense, the unit prices of the production factors used (inputs) and the products obtained (outputs) were determined to evaluate the relative economic and environmental impacts. The production cost analysis was carried out by examining its main components. To this end, the main "expense items" were aggregated according to a methodology widely established in economic–agrarian studies, where the elements of the production cost were divided into three macro-categories: "materials"; "work and services"; and "depreciation" and "other costs" [39,41]. The main cost item refers to costs related to the execution of works and the provision of external services in all of the scenarios examined; meanwhile, quotas, which include expenses incurred for depreciation, maintenance and insurance of fixed and stock capital, represent the second largest cost item of the total production costs. Material costs (e.g., fertilizers, pesticides, fuels, water, electricity, etc.) are those which, compared to the other cost items, account for the smallest share of the total production costs. For the calculation of the total output value, the average production of olives for oil harvested and the oil yield were taken into account. Then, the judgments of economic–environmental convenience for the adopted sustainable olive production models were developed. With regard to the impacts related to the life cycle of olive production, the LCA analysis was carried out by following the internationally recognized methodology and regulated by the UNI EN ISO standards of the 14040:2006 group [42] (ISO 14044:2006). The data processing was conducted using the LCA software SimaPro (v. 9.3.0) and following the reference standard for LCA [43–45]. In particular, the LCA approach permits the users to obtain an assessment and quantification of the energy and environmental loads and the potential impacts associated with a process or product along the entire life cycle ("from cradle to grave"), including all the phases that make up the production process [38,46,47]. The importance of this method is due to its innovative approach, which consists of evaluating all phases of a process, as related and dependent [43,45,46]. The quantification of the impacts reached a very high level of detail, allowing us to obtain the information necessary to make judgments of convenience at all phases of the production process. By applying the LCA methodology, the sustainability and environmental impacts of the individual production phases of the olive management models were evaluated and quantified, comparing the three different irrigation management practices with RW (T1_RW, T2_RW and T3_RW) and conventional water sources (T1_FW, T2_FW and T3_FW).

3. Results

3.1. Treatment Wastewater Efficiency

Table 3 shows the physical–chemical and microbiological concentrations observed at the TW units (H-SSF and FWS) during the monitoring periods, i.e., Period I (September 2019–September 2020) and Period II (October 2020–September 2021). Table 3 also reports the average physical–chemical and microbiological concentrations of the FW in reference to the irrigation seasons of 2020–21. In particular, the quality of the WW treated showed a high variability linked to the presence in the farmhouse, conditioned by the COVID-19 pandemic. In particular, in Period II, these concentrations were decidedly lower than those recorded in Period I (i.e., when the COVID-19 pandemic peaked and the minimum numbers of customers at the farmhouse was reached), with average percentage reductions between −12% (BOD_5) and −78% ($N\text{-}NO_3$). Only the N_{org} showed an increase in the average input values at the H-SSF unit, from 6.1 to 23.0 mg/L. This is probably linked to an increase in the WW flow rates, as this increase has caused a reduction in their retention times in the Imhoff tank and, consequently, a reduction in the conversion processes of N_{org} to $N\text{-}NH_3$.

Table 4 reports the removal efficiency of the whole TW system for the reference periods (I and II) and for all of the observation periods together (September 2019–2021). In general, high efficiencies were obtained in the removal of all the chemical–physical and microbiological investigated parameters. A limited reduction in removal efficiency was observed in the Period II, except for BOD_5. In addition, high algal bloom was detected in the FWS unit which negatively affected the efficiency of TSS and organic matter removal. However, the TW system showed an increase in the percentages of samples that meet the limits set by Legislative Decree 152/2006 for discharging into surface water bodies and by the Ministerial Decree 185/2003 for irrigation reuse (Table 5).

Table 3. Average and standard deviation (in brackets) values of chemical–physical and microbiological parameters of the fresh water (FW) and at the inlet and outlet of each stage of the treatment wetland units (i.e., the horizontal subsurface flow, H-SSF; and the free water surface flow, FWS) during the monitoring periods (Period I, September 2019 and September 2020; and Period II, October 2020 and September 2021). n.d. means not detected.

Parameter	Period I							Period II						Unit
	FW (2020–21)	Inlet H-SSF		Outlet H-SSF		Outlet FWS		Inlet H-SSF		Outlet H-SSF		Outlet FWS		
EC	2806.0 (±68.0)	3276.0	(±163.0)	2928.0	(±311.0)	2784.0	(±808.0)	2855.0	(±827.0)	3203.0	(±932.0)	3495.0	(±923.0)	µS/cm
pH	6.9 (±0.0)	6.8	(±0.4)	7.3	(±0.3)	7.5	(±0.3)	7.2	(±0.2)	7.3	(±0.2)	7.5	(±0.2)	-
TSS	3.0 (±0.0)	162.0	(±64.0)	38.0	(±23.0)	31.0	(±19.0)	66.0	(±32.0)	13.0	(±4.0)	17.0	(±21.0)	
COD	8.0 (±1.0)	746.0	(±215.0)	99.0	(±90.0)	71.0	(±56.0)	507.0	(±254.0)	53.0	(±26.0)	52.0	(±27.0)	
BOD_5	5.0 (±1.0)	432.0	(±123.0)	54.0	(±54.0)	38.0	(±29.0)	382.0	(±158.0)	42.0	(±18.0)	24.0	(±8.0)	
$N\text{-}NH_3$	<0.1	60.0	(±15.0)	18.0	(±7.0)	5.4	(±3.7)	49.0	(±20.0)	14.0	(±12.0)	5.5	(±5.3)	
$N\text{-}NO_2$	1.0 (±0.1)	8.0	(±12.0)	0.2	(±0.4)	0.1	(±0.2)	5.0	(±7.0)	0.0	(±0.0)	0.1	(±0.2)	mg L^{-1}
$N\text{-}NO_3$	<0.1	41.0	(±36.0)	5.0	(±10.0)	0.1	(±0.3)	9.0	(±14.0)	3.0	(±10.0)	0.1	(±0.2)	
N_{org}	0.3 (±0.1)	6.1	(±1.7)	0.9	(±0.5)	0.5	(±0.2)	23.0	(±28.0)	2.6	(±3.9)	1.5	(±1.5)	
N_{tot}	1.4 (±0.1)	115.0	(±14.0)	24.0	(±14.0)	6.1	(±3.7)	81.0	(±49.0)	21.0	(±18.0)	6.1	(±4.5)	
$P\text{-}PO_4$	0.3 (±0.0)	34.0	(±11.0)	20.0	(±8.0)	11.0	(±8.0)	16.0	(±12.0)	9.0	(±8.0)	7.0	(±8.0)	
E. coli	n.d.	n.d.		n.d.		n.d.		7.4	(±0.3)	5.7	(±1.1)	4.4	(±1.4)	$\log_{10}$ CFU 100 mL^{-1}

Table 4. Average removal efficiencies (%) of chemical–physical and microbiological parameters detected in the treatment wetland in the monitoring periods (Period I, September 2019 and September 2020; Period II, October 2020 and September 2021; and all periods together). n.d. means not detected.

Parameter	Period I	Period II	All Periods	Unit
TSS	82	71	75	
COD	90	83	88	
BOD_5	90	93	91	
$N\text{-}NH_3$	91	89	90	
$N\text{-}NO_2$	89	86	87	%
$N\text{-}NO_3$	100	68	83	
N_{org}	92	80	86	
N_{tot}	94	92	93	
$P\text{-}PO_4$	67	52	59	
E. coli	n.d.	3.0	3.0	$\log_{10}$ CFU 100 mL^{-1}

Table 5. Percentages (%) of samples collected at the inlet and outlet of the treatment wetland at the Valle dei Margi farmhouse, which agreed with the limits set by the Italian Legislative Decree 152/2006 and the Ministerial Decree 185/2003.

Parameter	Italian RW Discharge Limit [(1)] (mg/L)	Italian RW Reuse Limit (mg/L)	Inlet		Outlet	
			% Samples within the Limits for Discharge	% Samples within the Limits for Reuse	% Samples within the Limits for Discharge	% Samples within the Limits for Reuse
TSS	150 [(2)]	10	75	0	100	35
COD	125	100	5	0	95	95
BOD_5	25	20	0	0	57	43
N_{tot}	15 [(3)]	35	0	6	94	100

[(1)] The analyzes at the outlet from lagooning or treatment wetlands must be carried out on filtered samples; [(2)] limit of 150 mg/L for treatment wetlands and lagooning systems; [(3)] limit valid only for sensitive areas.

3.2. Irrigation Volumes and Water Savings

During the irrigation seasons of 2020–21, the application of the DI strategies allowed us to obtain water savings up to 50% and 20% under the SDI (T3) and PRD (T2), respectively, compared to the control full irrigation treatment (T1). In both irrigation sectors (FW and RW), the EU was above 94%.

Figure 3 shows the comparison between the cumulative irrigation volumes supplied and those estimated using the FAO-56 approach during the irrigation seasons of 2020–21. Note that limited deviations in the last part of the irrigation season of 2020 (August) were caused by the irrigation system malfunctions (Figure 3a). In 2021, an overall good alignment was obtained between the supplied and estimated irrigation volumes, with a slight underestimation of 7% observed at end of the irrigation season (September) (Figure 3b). At the irrigation sector level, underestimations of 13% and 2% were observed between the supplied and the estimated irrigation volumes, respectively (Figure 3c,d).

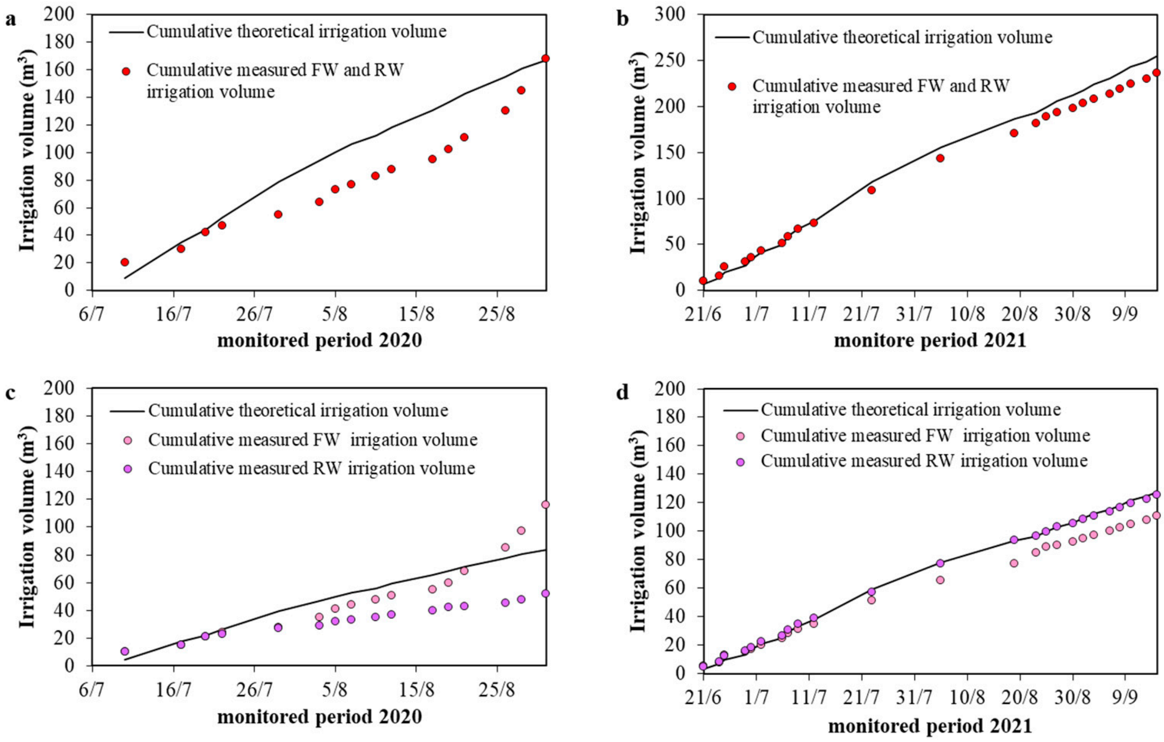

Figure 3. Overall cumulative theoretical and applied irrigation volumes (m^3) during the irrigation seasons of 2020 (**a**) and 2021 (**b**); cumulative theoretical and applied irrigation volumes at freshwater (FW) and reclaimed water (RW) irrigation sectors in 2020 (**c**) and 2021 (**d**).

3.3. Crop Water Status Response

3.3.1. Ground-Based Physiological Indicators

The Ψ values depict different behavior for the olive varieties at T1, both under FW (Figure 4a) and RW (Figure 4b) strategies during the irrigation season of 2021. In particular, almost constant Ψ values were observed under FW for "Nocellara Etnea" and "Carolea", while "Moresca" and "San Benedettese" were more sensitive to the higher T_{air} of August (Figure 4a). Nevertheless, these latter varieties returned to the Ψ levels of the other varieties when the T_{air} decreased and rain occurred in September 2021 (Figure 1). As observed for FW, the cvs. "Nocellara Etnea" also showed a better response under RW (Figure 4b). A certain sensitivity in "Carolea" and "Moresca" was observed, while "San Benedettese", in July, was less tolerant to the irrigation with RW.

No statistical differences were observed in terms of the RWC for the olive varieties under study and subjected to the different water management practices (Figure 5). In particular, the RWC ranged from 56.8% in the leaves of "Carolea" irrigated with RW to 61.8% for the same cultivar under FW conditions.

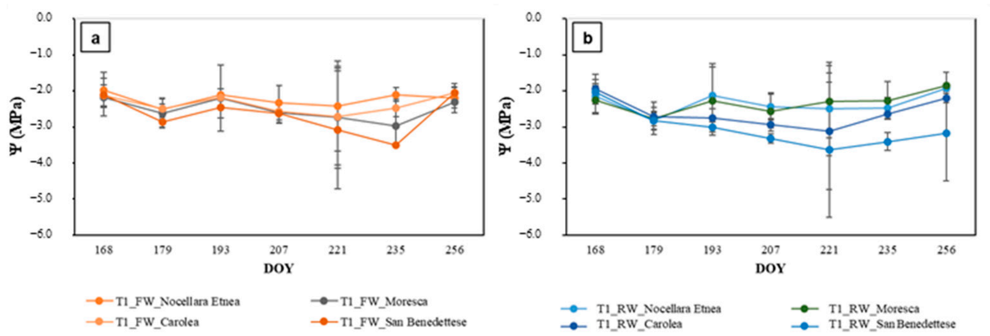

Figure 4. Leaf water potential (Ψ, MPa) trends observed at the control treatment (T1) under (**a**) freshwater (FW) and (**b**) reclaimed water (RW) strategies during the irrigation season of 2021 for the 4 olive cultivars under study.

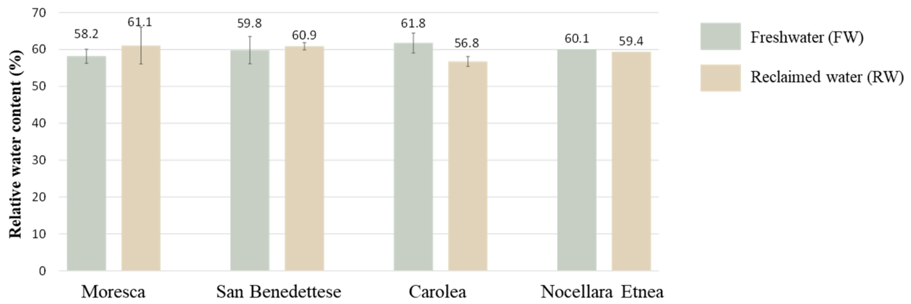

Figure 5. The relative water content (RWC, %) of the different olive cultivars irrigated with fresh water (FW) and reclaimed water (RW), respectively.

3.3.2. Satellite-Based Biophysical Indices

A general increase in the values of the satellite-based indicators (albedo, NDVI and LAI) was observed during the irrigation seasons under study (2020–21), in comparison to the temporal phase before the application of the sustainable irrigation practices (i.e., 2019) (Figure 6).

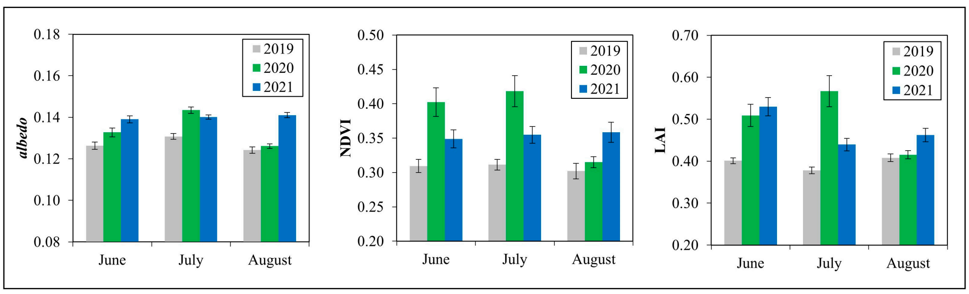

Figure 6. Average and standard error values of the satellite-based biophysical indices (albedo, NDVI and LAI) for the olive grove under study (2019–2021).

Figure 6 demonstrates an overall positive effect linked to the combination of DI strategies and the RW as sources of irrigation. An example of the spatial distribution of the obtained biophysical indices at the treatments T1–T3 under FW and RW are reported in Figure 7 for the same period (July) during the irrigation seasons 2020–21. At the treatment level, a slight decrease in the average values of the NDVI and LAI indices was proportional to the increase in the applied water deficit at T2 and T3 (from 20% to 50%) (Supplementary Figures S1 and S2). However, no differences were found in 2020–21 among all the biophysical indices analyzed in the two irrigation sectors (FW and RW), even under different irrigation regimes (T1, T2 and T3).

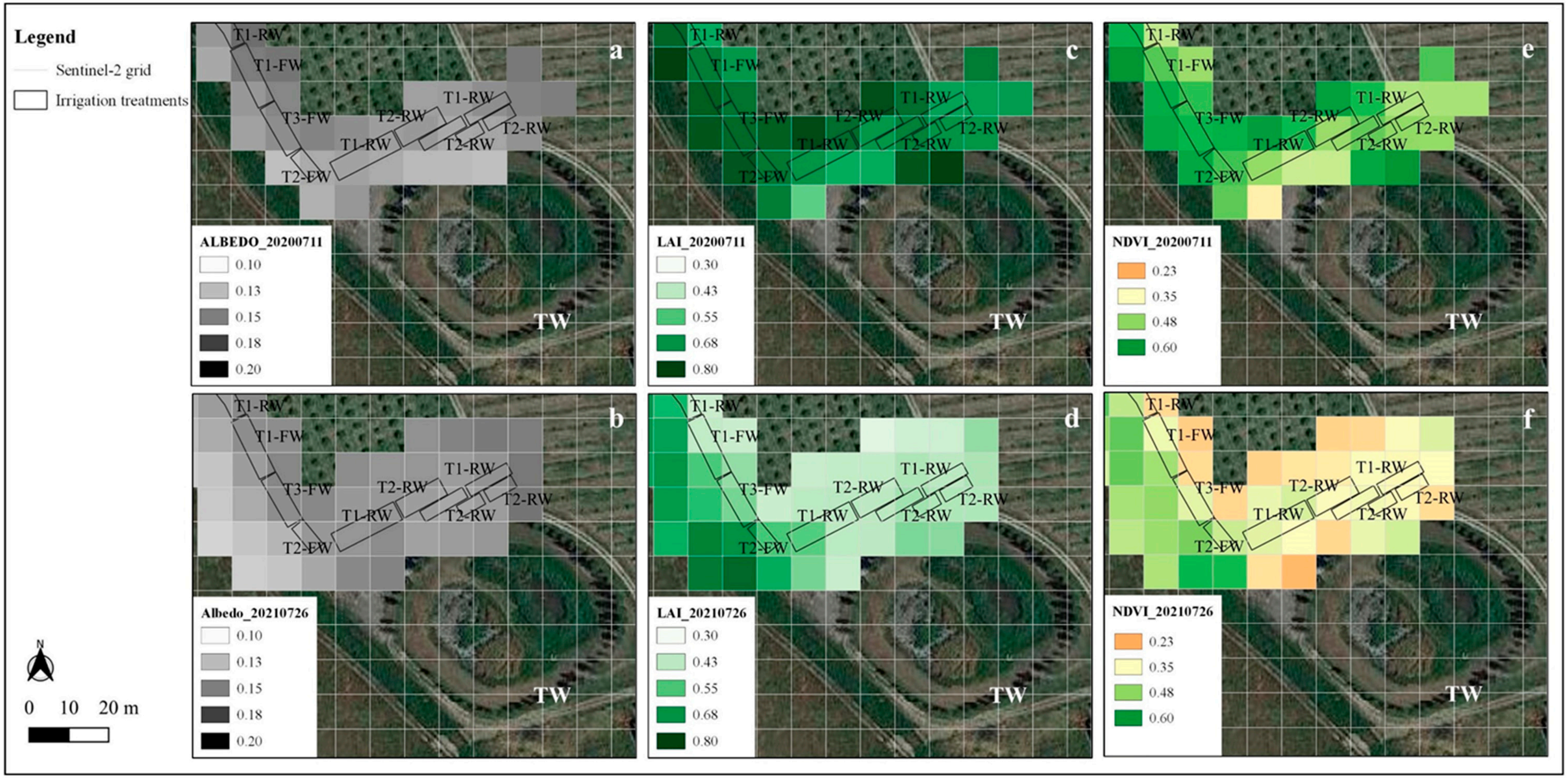

Figure 7. Spatial distribution of the biophysical indices: albedo (**a**,**b**), LAI (**c**,**d**) and NDVI (**e**,**f**) at the treatments under study (T1–T3) under fresh water (FW) and reclaimed water (RW) for selected dates in 2020 and 2021. TW refers to the treatment wetland system.

3.4. Effects on Olive Oil Qualitative Parameters

The fatty acid composition of the olive oil under the experimental condition is exhibited in Figure 8. In particular, a total of 11 fatty acids were identified, and their relative proportions were quantified (in percentages, %) in all samples for the treatments used in the study (FW versus RW).

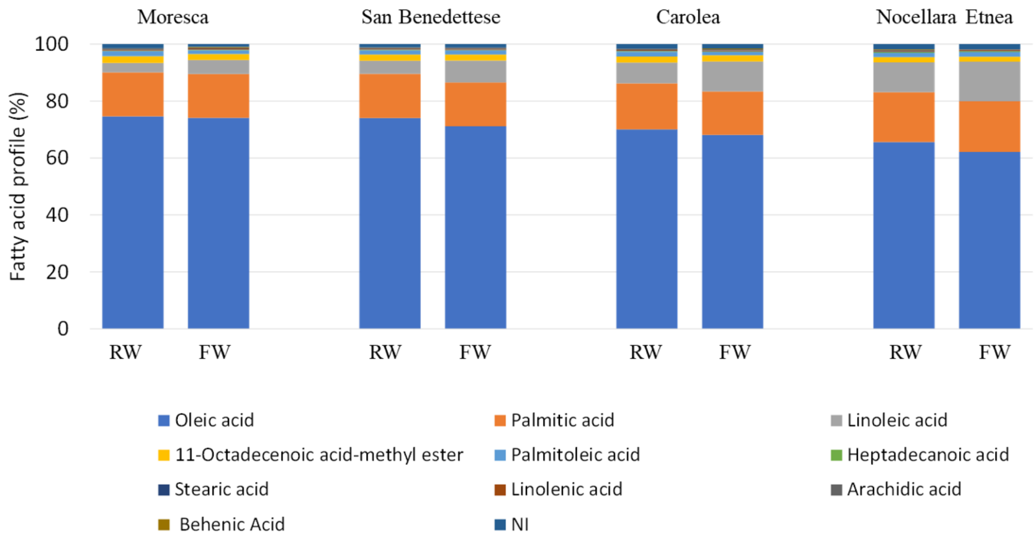

Figure 8. The profile of fatty acids (%) in the oil of the different olive cultivars irrigated using different water treatments. FW, fresh water; RW, reclaimed water; NI, unidentified compounds.

As expected, the main compound was oleic acid (with an average of 69.1%), followed by palmitic acid (with an average of 16.0%), and stearic acid was the lowest constituent (with an average of 0.1%) under FW and RW conditions. The highest concentration of oleic acid was observed in the cultivar "Moresca" under FW and RW conditions (~74.6%). All the other cultivars, with the exception of "San Benedettese", had a lower content of oleic acid, and the least amount was found in cv. "Nocellara Etnea" under RW. Specifically, "San Benedettese", "Carolea" and "Nocellara Etnea" revealed lower values of oleic acid under RW (71.2, 68.1 and 62.1%, respectively) than under FW treatments (74.1, 70.1 and 65.6%, respectively). Palmitic acid, the second fatty acid after oleic acid, presented a higher % in the cv. "Nocellara Etnea" under RW (17.3%), while "Carolea" showed the lowest amount (15.3%). Linoleic acid was higher in the RW treatments. Regarding the other fatty acids, no relevant differences in quantities were observed.

3.5. Economic and Environmental Assessment of the Sustainable Irrigation Practices

The economic and environmental assessment, comparing the irrigation management strategies (T1, T2 and T3) using FW and RW, respectively, resulted in six different scenarios (Tables 6 and 7).

In absolute terms, the T2_FW scenario represented the lowest unit production cost per kg of oil. The T2_RW scenario showed the highest incidence of costs for "works and services", while the scenario with the lowest incidence was T3_FW. In more detail, the overall production cost for the T1_FW scenario was EUR 3164.55/ha, corresponding to a cost per kg of oil of EUR 4.94. In particular, by analyzing the values of the single components of the production cost, the cost of the execution of "works and services" under the T1_FW scenario was equal to 1443.59 EUR/ha, with slightly lower costs attributable to the items "quotas and other allocations" (1289.39 EUR/ha) and "materials" (431.57 EUR/ha). The T2_FW scenario showed a slighter increase in production costs (EUR3761.48/ha) in comparison to T1_FW, corresponding to a cost per kg of oil of EUR 4.37. In this scenario, the costs for "works and services" were 50% higher than they were for the rest of the items. Under the T3_FW scenario, the unit costs per hectare decrease slightly compared to the other FW scenarios; even this scenario showed the highest unit cost of production (5.18 EUR/kg). The scenarios involving the use of RW, in all three water regimes considered (T1, T2 and T3), although showing a higher level of production costs, resulted in being more efficient, showing a slightly lower cost per kg of oil, because the use of RW required a lower energy cost in comparison to the use of FW for irrigation purposes.

Table 6. Economics analysis under freshwater (FW) scenarios for the different water regimes (T1–T3).

Indications	T1_FW		T3_FW		T3_FW	
	EUR/ha	EUR/kg Olive Oil	EUR/ha	EUR/kg Olive Oil	EUR/ha	EUR/kg Olive Oil
-Revenues	4165.93	6.50	5594.06	6.50	3948.75	6.50
-CAP direct payment	210.00	0.31	210.00	0.24	210.00	0.28
Total Output Value	4375.93	6.81	5804.06	6.74	4158.75	6.78
-Materials	431.57	0.67	471.17	0.55	459.15	0.76
-Labor and services	1443.59	2.58	1873.23	2.50	1410.68	2.65
-Depreciation and other costs	1289.39	1.69	1417.07	1.32	1278.94	1.78
Total Cost	3164.55	4.94	3761.48	4.37	3148.77	5.18
Net Value	1211.38	1.88	2042.58	2.37	1009.98	1.60

Table 7. Economics analysis under reclaimed water (RW) scenarios for the different water regimes (T1–T3).

Indications	T1_RW		T2_RW		T3_RW	
	EUR/ha	EUR/kg Olive Oil	EUR/ha	EUR/kg Olive Oil	EUR/ha	EUR/kg Olive Oil
-Revenues	4339.24	6.50	5747.63	6.50	4830.64	6.50
-CAP direct payment	210.00	0.31	210.00	0.24	210.00	0.28
Total Output Value	4549.24	6.81	5957.63	6.74	5040.64	6.78
-Materials	407.05	0.61	412.26	0.47	485.20	0.65
-Labor and services	1658.41	2.81	1890.92	2.46	1749.38	2.68
-Depreciation and other costs	1346.49	1.69	1422.37	1.28	1376.81	1.53
Total Cost	3411.96	5.11	3725.55	4.21	3611.38	4.86
Net Value	1137.28	1.70	2232.07	2.52	1429.26	1.92

Regarding the quantities of olives harvested, the oil produced and the corresponding average price recorded, the gross salable production reached an average value of 4375.93 EUR/ha, 5804.06 EUR/ha and 4158.75 EUR/ha for the T1_FW, T2_FW and T3_FW scenario, respectively (Table 6). This production value, when measured according to the kg of oil, varied from 6.81 EUR/kg to 6.74 EUR/ha and 6.78 EUR/ha for the T1_FW, T2_FW and T3_FW scenario, respectively. The analysis of the gross salable production for the three scenarios with the use of RW provided improved results in comparison to the FW condition due to the higher yield of olives obtained as unit values per hectare of surface, which amounted to 4549.24 EUR/ha, 5957.63 EUR/ha and 5040.64 EUR/ha for the T1_RW, T2_RW, T3_RW scenario, respectively (Table 7).

Net farm incomes, which represent the degree of remuneration of production factors, recorded positive values, with higher amounts for the RW scenarios. Overall, the T1_RW scenario reported the highest value of the unit of product (6.81 EUR/kg), while T2_RW showed the lowest total output value (6.74 EUR/kg) and the highest net value per kg of oil. However, T2_RW manages to optimize all the factors of oil production, reaching the highest levels of company net income. In fact, in the T2_RW scenario, the company's net income stands at 2232.07 EUR/ha, corresponding to a value of 2.37 EUR per kg of oil. Under RW conditions, the T2 scenario is capable of remunerating the factors of production used to a greater extent at market prices. In fact, the net income stands at 2232.07 EUR/ha and 2.52 EUR/kg of oil produced.

The results of the LCA analysis show a significant reduction in the impacts of the irrigation treatments that use RW, which is particularly evident in the water consumption impact category (Figures 9 and 10). Furthermore, between the three different hypothesized scenarios of water deficit application (from 20 to 50% of water deficit), a reduction in the water consumption impact was observed, ranging from T1 to T3.

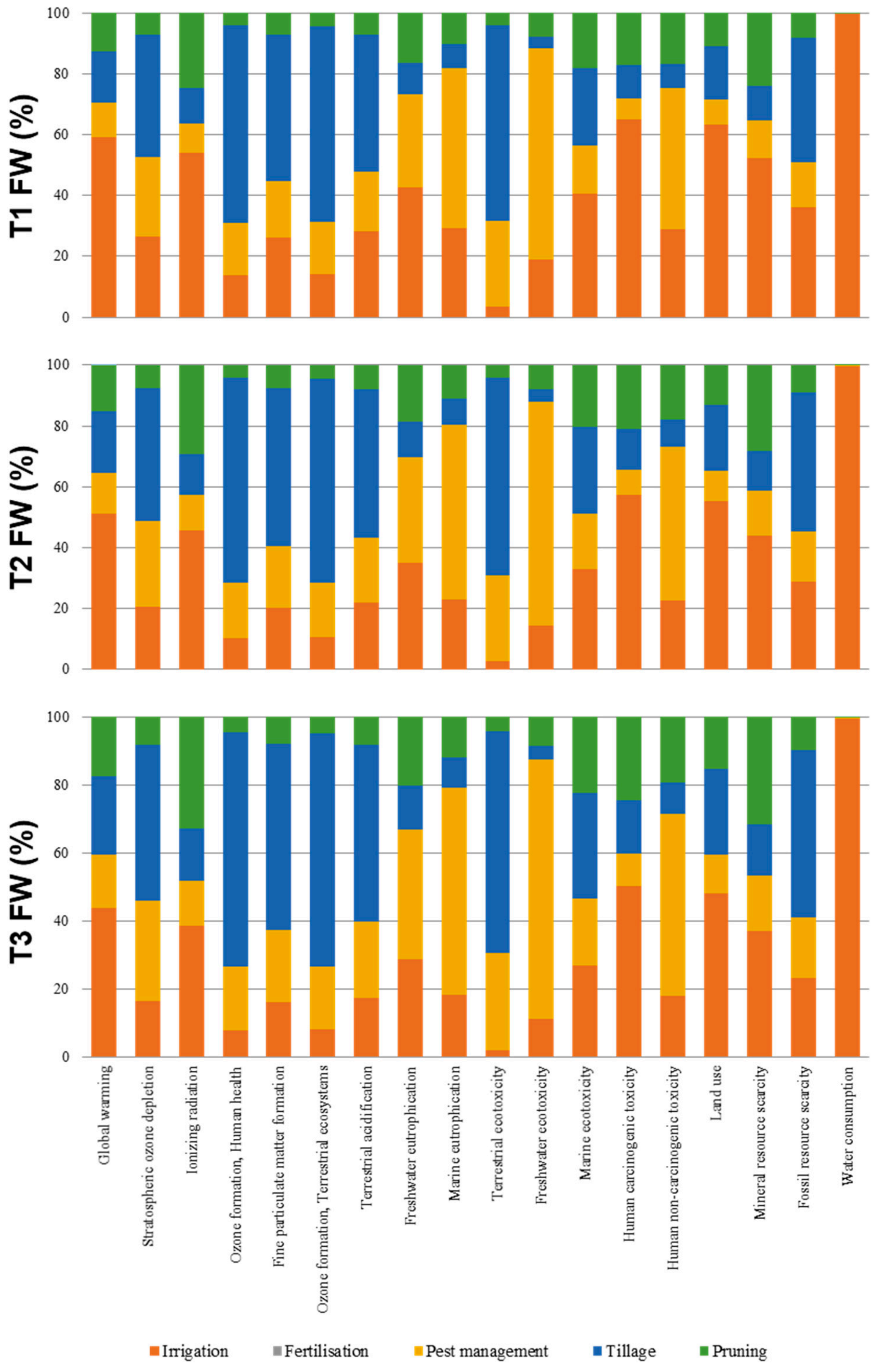

Figure 9. Environmental impacts per treatment per agronomic operation (%) under the freshwater (FW) scenario.

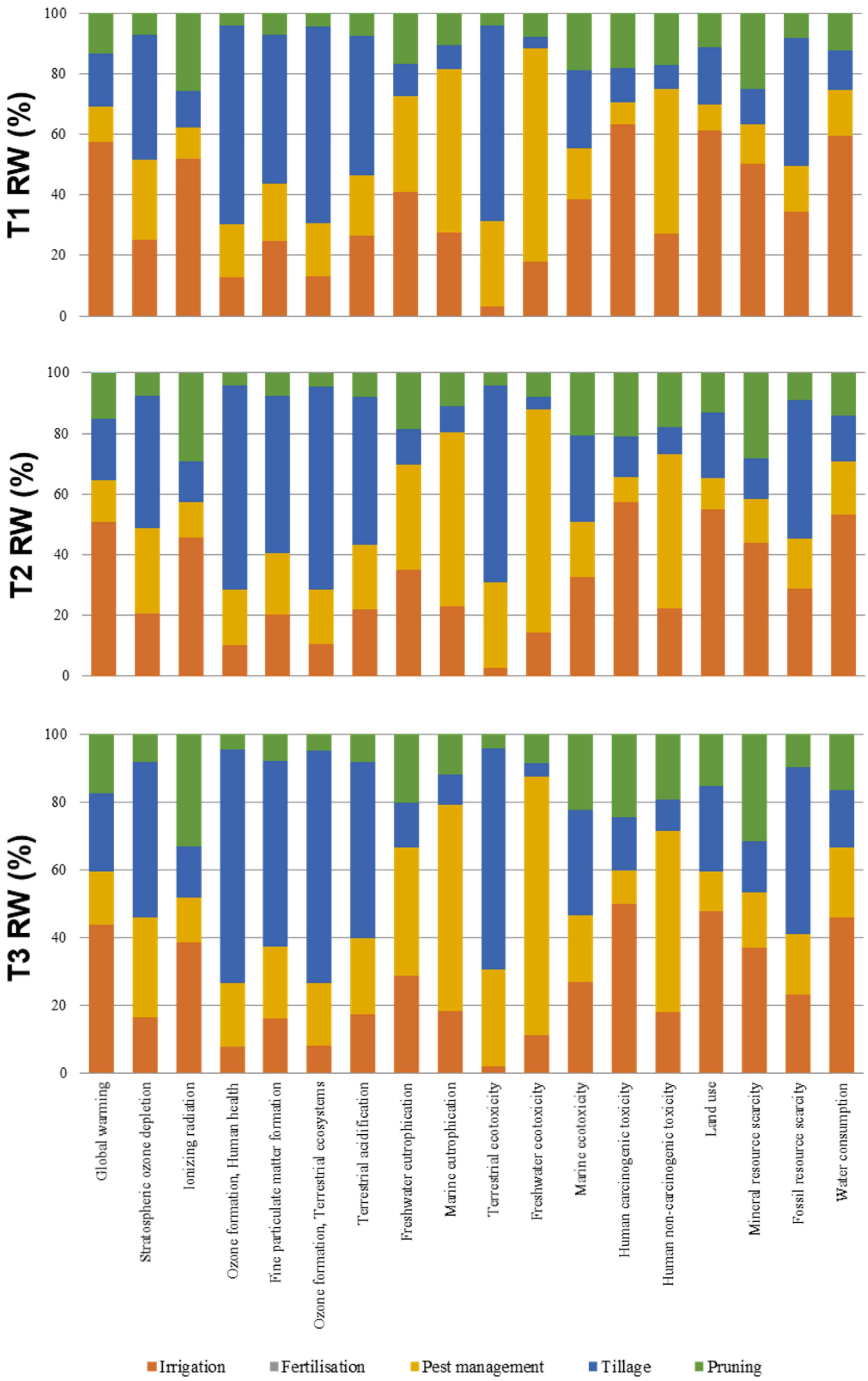

Figure 10. Environmental impacts per treatment per agronomic operation (%) under reclaimed water (RW) scenario.

4. Discussion

Advanced methodologies for secondary and/or tertiary WW treatment, based on the use of nature-based solutions and/or on the integration of multiple reclamation technologies, have been developed and applied on a real scale [48,49]. In order for these technologies to be fully employed, it is highly required that we establish concrete policies and practices to encourage safe water reuse, taking advantage of its potential benefits for the agriculture sector [13,50,51]. In this study, despite limited exceptions for some parameters in specific periods characterized by the intermittent number of agritourism visits due to the COVID-19 pandemic emergency, the high removal efficiency of the TW system highlights the potential of adopting nature-based solutions as RW technology [52–54]. In particular, the study underlines the importance of conducting periodic monitoring and maintenance operations of the TW system [23,55]. It should be noted that the exceeding of the regulatory limits in the effluents of the TW system was mainly detected in samples that were taken when the concentration of organic matter influent was about double that of the ones design and/or following specific events of alteration of the bacterial flora of the plant, such as extraordinary maintenance, breakdowns or reduced WW flow due to the absence or reduced presence of customers in the agritourism. In this sense, for the use of RW for irrigation purposes, it would be advisable to integrate the in situ TW system into the two phases of the FWS unit [56]. For this purpose, a filter layer, characterized by inert material with a texture between 2 and 5 mm, may be introduced into the final section of the FWS unit to promote the filtration process of the effluent before its reuse.

Irrigation sustainability in traditional olive orchards needs to consider several aspects to ensure an efficient water management regime [57]. A number of studies have analyzed the effects associated with the application of RW on olive groves, in combination with DI strategies, as an alternative water source for irrigation (Supplementary Table S1). Some studies highlighted the importance of analyzing the medium- and long-term effects both at the plant and soil level [58–60]. However, few studies proposed integrated methodologies to assess the interdisciplinary issues related to water use when supplying water to olive plantations, focusing solely on the surface and groundwater sources [61].

In this study, we propose a combined approach for evaluating the sustainability of a Mediterranean olive grove under different water reuse scenarios from a multi-perspective point of view, e.g., analyzing different aspects ranging from the determination of the CWS (i.e., using ground- and satellite-based methods) to the evaluation of the economic and environmental features. Specifically, the ground-based physiological indicators showed a strong impact on the variation in Ψ among the four analyzed cultivars, indicating that their performances are greatly dependent on the genotype. Specifically, each variety seemed to have specific watering needs and less or greater adaptability to the use of RW. As an example, the cvs. "Nocellara Etnea" showed a better response both under FW and RW. This should depend on the water salinity (EC), considering that the FW had a slightly lower EC than the RW (Table 3). No differences were observed in the leaves' RWC among the different olive cultivars, both under FW and RW conditions, showing a great adaptability of the olive trees to the different irrigation regime. This evidence is supported by the satellite-based biophysical indices (albedo, NDVI and LAI) that did not show differences among the treatments under study, even under levels of applied water deficit up to 50% (T3). This behavior depends on whether the trees under study did not experience water stress levels that were too high to be detected by the satellite-based indices at the available spatial resolution [62]. The use of remote sensing applications may be enhanced by adopting UAV tools to monitor the effects of cumulative stress in olive orchards at a higher spatial resolution [63].

Regarding the olive oil composition, the fatty acid profile was mainly affected by the different irrigation treatments, as well as by the agronomic management, the maturity degree of olives and the cultivar [64–66]. Note that the composition of fatty acids is mainly affected by geographical conditions (location, climate and latitude), ripening degree, season and production; it also depends on the genotype [67]. Indeed, several studies reported that the most prevalent fatty acid in virgin olive oil is oleic acid, as it accounts for about 68–82% of the total fatty acids [68–70]. Specifically, the percentage of oleic acid obtained in this study confirmed the results provided by [71,72].

Moreover, a practical step forward of this study consisted in formulating cost-effectiveness judgements to assess the sustainable development of olive growing systems under the Mediterranean environment under the use of RW. The results of the LCA analysis underlined that the use of RW allows us to achieve huge economic and environmental savings. This is a key aspect to take into consideration since the economic sustainability cannot be separated from the environmental stability when encouraging the more sustainable management of the olive production system. Finally, the main advantages and the future outlook proposed to overcome possible limitations of the multiple methodological approaches described in this study are summarized in Table 8.

Table 8. Advantages and future outlook of this study.

Topics	Advantages and Findings	Future Outlook
Treatment wastewater efficiency	Higher removal efficiency is obtained when the TW system was at full operation condition (i.e., in 2021)	To perform maintenance operations and integrate the TW system with two phases of the FWS unit
Reclaimed water under DI context	Water savings up to 50% and 20% are reached under the T2 and T3, respectively	To conduct long-term experiments to evaluate the effects of water deficit both at the plant and soil level
Crop water status	The leaf water potential reflects a different behavior among the genotypes "Nocellara Etnea" shows a better response both under FW and RW	
	No differences were observed on the biophysical indicators analyzed at the treatment level	To UAV imagery for enhancing the spatial resolution of the applied remote sensing approach
Economic and environmental assessment	Reduction in the economic impacts related to the irrigation treatments that use RW	To acquire a site-specific economic dataset for each local context

5. Conclusions

The main findings that can be drawn from this study are listed as follows:

(i) The application of DI strategies allowed us to obtain water savings up to 50% and 20% under the PRD (T2) and SDI (T3), respectively, compared to the control treatment (T1), under both FW and RW conditions. These findings are translated into both economic and environmental advantages;

(ii) Different olive cultivars under FW and RW determine a certain degree of variability both in terms of crop response (Ψ) and fatty acid composition;

(iii) No differences were found for the RWC of the leaves under FW or RW scenarios. This behavior was also reflected in terms of satellite-based indicators;

(iv) A significant reduction in the economic impacts of the water deficit regimes was obtained using RW. Specifically, the T2_RW scenario was capable of remunerating the factors of production used to a greater extent at market prices.

In conclusion, periodic monitoring and maintenance operations are recommended to guarantee a high removal efficiency of the overall TW system and to improve the quality of the RW for irrigation purposes. This necessity is particularly urgent when the WW load is inconstant (during the COVID-19 pandemic period). Finally, the use of RW can allow us to achieve huge water savings, (e.g., an economical and environmental gain), representing an added value for olive growing to operate according to more sustainable development models.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152015101/s1, Table S1: Summary of the main findings concerning the adoption of reclaimed water (RW) for olive trees. Figure S1: Average and standard error values of the satellite-based biophysical indices (albedo, NDVI and LAI) at the different irrigation sectors in 2020. Figure S2: Average and standard error values of the satellite-based biophysical indices (*albedo*, NDVI and LAI) at the different irrigation sectors in 2021. References [20,58–60,62,73–84] are cited in the supplementary materials.

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Conflicts of Interest: The authors declare no conflict of interest.

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