WP#5

Deliverable 5.4.1

Water-energy-food (WEF) Nexus

Interreg V- A Greece-Italy Programme 2014 2020

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IR$_2$MA
Large Scale Irrigation Management Tools for Sustainable Water Management in Rural Areas and Protection of Receiving Aquatic Ecosystems

Subsidy Contract No: I1/2.3/27

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Partners

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Notes

Deliverable 5.4.1 - Water-energy-food (WEF) Nexus

A nexus life cycle thinking-based performance assessment: From water supply to crop production in Sinistra Ofanto (Southern Italy)

Involved partners:

PB4 CIHEAM - ISTITUTO AGRONOMICO MEDITERRANEO – BARI (IAMB)

PB2 ISTITUTO SCIENZE DELLE PRODUZIONI ALIMENTARI (ISPA/CNR)

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Place and time: Italy, 2020

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Contents

Figures

Tables

Summary

This study conducted in the framework of the IR2MA project analyzed water–energy-environment (WEEN) nexus trade-offs and synergies of water supply and crop production in irrigation districts of the Sinistra Ofanto irrigation system. Two case studies were developed. First, it analyzed the benefits and trade-offs of wastewater reuse in front of a non-reuse scenario in district 17 of Trinitapoli (41°210 N, 16°030 E). An integrated analytical indicator framework with physical and monetized life cycle assessment (LCA) and sustainability SWOT (Strengths, Weaknesses, Opportunities, Threats) was used for the assessment. The WEEN analysis generated a wider understanding and awareness of water supply practices and sustainability implications in an Italian and Mediterranean context using numerous impact categories and combining both costs and environmental loads in one single assessment. Secondly, a complete evaluation of the crop production system/s was performed for irrigation district 1-a using a Water-Energy-Food-Environmental (WEFE) nexus. This holistic analysis provided nexus information between irrigation and other farm management practices. The overall results of the study were useful for the evaluation of the nexus-sustainability of intensive agricultural areas in Southern Italy.

Keywords: large-scale irrigation systems, water-energy-environment nexus, life cycle assessment, monetary valuation, sustainability;

Riassunto

Questo studio condotto nel quadro del progetto IR2MA ha analizzato il nesso acqua-energia-ambiente (WEEN) e compromessi e le sinergie di approvvigionamento idrico e produzione agricola nei distretti irrigui del sistema di irrigazione Sinistra Ofanto. Sono stati sviluppati due casi di studio. In primo luogo, sono stati analizzato i vantaggi e i compromessi del riutilizzo delle acque reflue a fronte di uno scenario di non riutilizzo nel distretto 17 di Trinitapoli (41 ° 210 N, 16 ° 030 E). Per la valutazione è stato utilizzato un quadro di indicatori analitici integrati con valutazione del ciclo di vita(LCA) fisico ed economico e SWOT di sostenibilità (punti di forza, debolezze, opportunità, minacce). L'analisi WEEN ha generato una più ampia comprensione e consapevolezza delle pratiche di approvvigionamento idrico e delle implicazioni di sostenibilità in un contesto Italiano e Mediterraneo utilizzando numerose categorie di impatto e combinando costi e carichi ambientali in un'unica valutazione. In secondo luogo, è stata eseguita una valutazione completa delle colture per il distretto irriguo 1-a utilizzando un nesso Acqua-Energia-Cibo-Ambiente (WEFE). Questa analisi olistica ha fornito informazioni sul nesso tra l'irrigazione e altre pratiche di gestione agricola. I risultati complessivi dello studio sono stati utili per la valutazione del nesso-sostenibilità delle aree agricole intensive nel Mezzogiorno.

Parole chiave: sistemi di irrigazione su larga scala, nesso acqua-energia-ambiente, valutazione del ciclo di vita, valutazione monetaria, sostenibilità;

1. Introduction

Water is the main issue in the political and administrative agenda of the Apulia region, as it is essential for its agricultural sector, encompassing almost 352.000 farms (IPA-CBC 2016). Sinistra Ofanto is one of the greatest and most important multi-cropped irrigated areas in the Apulia and the whole Mediterranean region (Todorovic et al. 2016). The area is facing context-specific challenges associated with a change in cropping pattern concerning the design stage, intensive agricultural activities, increasing droughts, and water scarcity leading to limited surface water resource availability and over-exploitation of groundwater (Giordano et al. 2010; Levidow et al. 2014). In this context, efficient irrigation practices are becoming essential for sustaining crop production and socio-economic welfare. However, water-efficient agriculture has resulted in unsustainable exploitation of water resources due to the adoption of more water demanding crops. At the same time, due to the unquestionable link between water and energy resources, high amounts of energy consumption are associated with freshwater supply with a consequent increase in energy use and economic cost (Belaud et al., 2020). As a consequence, the management of water resources is expected to challenge not only freshwater resources but also energy source constraints in many countries (Espinosa-Tasón et al., 2020). The provision of water and energy services could cause significant negative environmental impacts in large-scale pressurized irrigation systems. Also, energy consumption for irrigation has major environmental implications due to fossil fuel combustion or high fossil-energy use in electrical grids (Pradeleix et al., 2015).

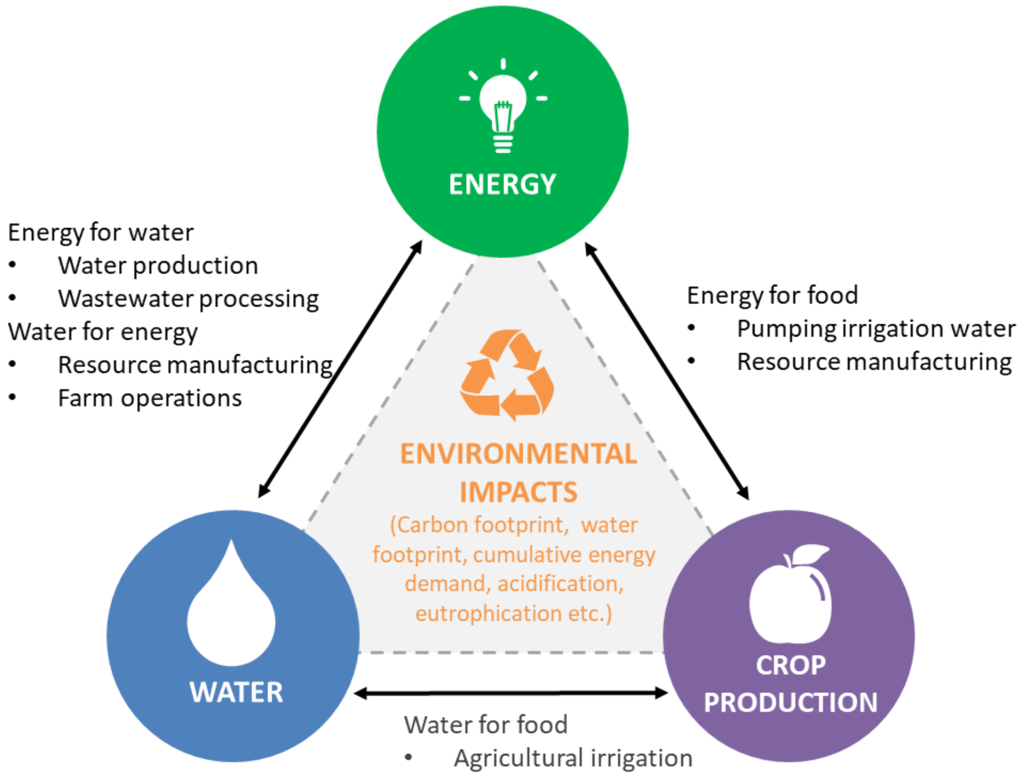
The interdependencies between water, energy, and environmental impacts in irrigated agriculture are commanding increasing attention. This is because water use and agricultural practices in the Mediterranean are becoming increasingly complex and unsustainable (Saladini et al., 2018). On a life-cycle basis, the inextricable links between the domains are often complex calling for a holistic and inclusive approach to address complex resource and development challenges (Momblanch et al. 2019). Interconnections, synergies, and trade-offs are common keywords within the nexus concept (Cabello et al. 2019) which is gaining increasing attention in sustainability research and policymaking communities (Cabello et al. 2019; Zhang et al. 2018a). The nexus and associated terminology is becoming an increasingly common framework for sustainability research in irrigated agriculture (Hamidov and Helming, 2020).

This study explores what the nexus is, and apply a nexus-oriented framework to generate a sustainability-oriented multidimensional analysis of irrigation water supply and crop cultivation in Sinistra Ofanto agricultural systems. Life cycle assessment (LCA) and sustainability SWOT (Strengths, Weaknesses, Opportunities, and Threats) were used for assessment.

2. Overview of the nexus concept

The global demand for water, energy, and food demand by 2050 due to both economic and population growth is exerting pressure on agriculture systems involving complex trade-off water and energy consumption, as well as environmental impacts. Food, water, energy, and the environment are highly interconnected resulting in numerous and substantial interactions (Fig. 1). In irrigated agriculture, the consumption of energy and water is essential for life and agricultural production processes (Jackson, 2009). At a basic level, crop production requires both water and energy; pumping, treating, and

transporting water requires energy; energy production requires water (Daher and Mohtar 2015). So, if you want more water, you need energy and vice versa (Schnoor 2011). Energy, water, and environmental problems are closely related, since it is nearly impossible to produce, transport, or consume water and energy without environmental impact. Water, carbon, or environmental footprint arises from resources (energy/fuel/water) production, transportation, and consumption on-farm (Tamburini et al. 2015). Interconnections, synergies, and trade-offs between two or more things are common keywords within the nexus concept (Cabello et al. 2019).



Source: Own elaboration based on Bieber et al. (2018).

Fig. 1. The interactions and potential synergies between water, food, energy, and environmental impacts.

The nexus concept gathered momentum within the broader sustainability debate during the 2008 World Economic Forum annual meeting (World Economic Forum, 2011a). Since then has gained increasing attention in the research communities and with international conferences as the security of water, energy and food becomes a very high concern due to future uncertainties. The nexus anyhow is not a new idea. Nexus-related conferences, research initiatives, and projects have taken place as early as the 1980s typically focused on strict water-energy interaction. Some milestones for the emergence of the nexus vision were the recognition of the climate change problem (2003-2011), nuclear disasters (1986, 2011), oil spills into the ocean, and development of bio-remediation (1986-2010), and the rise of biofuels and food markets inflation in (2006-2007). The increased use of the nexus approach in global discourse and debates about the natural resources and the lack of clarity and consensus related to the presentation of its concept and application have brought an increase of 79% in the use of the term nexus in scientific

papers (Torres et al. 2019). The water-energy-food and water-energy concepts are the most analyzed in scientific studies with 66% and 13.8%, respectively. All other compositions among the nexus elements achieved lower frequencies of participation in the reviewed papers (Torres et al. 2019). However, these concepts do not fully capture the components of the environment and their ecosystem services (Brusseau 2019), an important component of nexus. The analytical capacity of interactions among resources is expanding with increasing attention to water-energy-environment or water-energy-food-environment nexus practices. Still will all publications and processes, there is no general agreement on what the nexus is and what a "nexus approach" actually means and requires. According to 'nexus scope', there are five categories of nexus (Dai et al. 2018):

1) Water-energy nexus (WEN),
2) Water-energy-environment nexus (WEEN),
3) Water-energy-food nexus (WEFN),
4) Water-energy-food-ecosystem nexus (WEFEN),
5) Water-energy-land-climate nexus (WELCN).

Nexus studies are rapidly emerging in contemporary research performed on a very wide range of issues (resource scarcity, sustainable intensification, as well as climate change impacts), scales (micro vs. macro), and include the development of many models and calculation tools. In agriculture, issues such as irrigated agriculture, wastewater treatment, and reuse, food waste, agricultural water management are covered (Torres et al. 2019). Conduction of nexus assessment is driven by external factors classified into two groups: physical social causes (Zhang et al. 2018b). Physical factors are related to climate change, extreme weather, and natural hazards which may change the provision of water, energy, and food by influencing their supply chains and production processes. On the other hand, social factors such as user behavior and perception may move the focus of resources management from the supply side to the demand side.

2.1 The relevance of the nexus concept

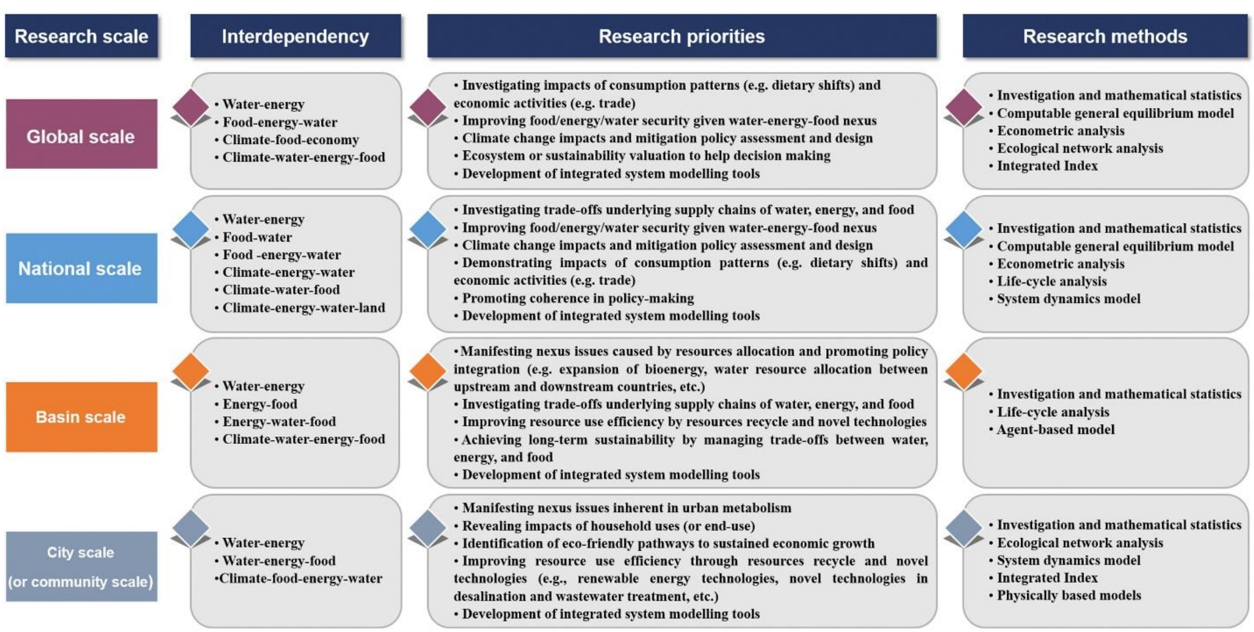
The nexus concept offers a holistic and inclusive approach to address complex resource and development challenges (Albrecht et al., 2018). Nexus thinking is relevant for integrated water resources management (Hamidov and Helming, 2020) and to use and manage resource systems taking into account different sustainability goals (Reinhard et al. 2017). It can jointly address growing water, energy, and food security challenges (Albrecht et al., 2018; Rasul and Sharma, 2016) and support policy-making (Brouwer et al., 2018). The nexus approach internalize social and environmental impacts and guide the development of cross-sectoral policies (Albrecht et al., 2018). The nexus field can also aid in achieving the United Nations Sustainable Development Goals 2 (Zero Hunger), 6 (Clean Water and Sanitation), and 7 (Affordable and Clean Energy) (Torres et al., 2019). This is translated into improved resource management and governance outcomes (Galaitsi et al., 2018).

2.2 Methods and tools available for nexus assessment

As an analytical tool, a nexus analysis system uses methods and tools to understand interactions among water, energy, and food systems (Albrecht et al. 2018). The assessment methods and tools included are:

- Qualitative - quantify the resource flows but without modeling scenarios over temporal scales.
- Quantitative - a single model for simulating scenarios over temporal scales.
- qualitative-quantitative - a combined model with both quantitative and scenario functions

Usually, nexus research questions are summarized into three themes: internal relationship analysis, external impact analysis, and nexus system evaluation (Zhang et al. 2018b). There have been numerous and diverse analytical tools that have been used or proposed to assess and implement the water, energy, food nexus approach of management. The most widely used modeling approaches fall under the following categories (Fazekas et al. 2017): i) Computable General Equilibrium (CGE) models; ii) Partial equilibrium models; iii) Macro-econometric models; iv) Bottom-up engineering models; v) Climate models; vi) Large-scale and Small Scale Integrated Assessment Models; vii) Agent-based models; viii) Bayesian network models; ix) Systems dynamics models. Methods that originate from the fields of environmental management and economics are commonly utilized (Albrecht et al. 2018). In most cases, the models operate through a scenario-based approach. A detailed description of each nexus research method listed in Fig. 2 is provided by Albrecht et al. (2018). Other reviews of the available methodologies introduced in the last few years can be found elsewhere (Chang et al. 2016; Endo et al. 2017; Kurian 2017).



Retrieved from Zhang et al. (2018)

Fig. 2. Summary of nexus research methods and their applications.

Since each nexus case is unique and no versatile and comprehensive modeling approach fits modeling and quantifying every case. The appropriate methods vary in response to the scale and research priorities of

a specific nexus system (Fig. 2). The nexus is complex and exists on many scales, from the global and national scale down to the end-user. From 2018 to 2019, the usage of global-scale studies decreased, and the regional scale and basin-scale increased (Torres et al. 2019). Specific tools frequently used in basin-scale include life-cycle assessment (LCA), input-output analysis, trade-off analysis, or integrated mathematical models with scenario analysis (Zhang et al. 2018b).

There have been several computation tools (Table 1) developed by leading international organizations and agencies to assess and adopt the water-energy-food nexus approach of management (Shinde 2017). The tools under are classified into three categories: understanding the nexus, governing the nexus, or implementing the nexus (Dai et al., 2018). Existing Nexus tools: are classified as quantitative (e.g. CLEWs, WEAP-LEAP, FAO, AquaCrop, SimaPro, Foreseer tool) or qualitative and semi-qualitative tools (e.g. MuSIASEM and FAO). These nexus tools exist differ from inputs, outputs, or analytical characteristics.

Table 1. Classification of nexus methods according to their nexus scope, model type, and nexus challenge level.

Nexus challenge	Method type		
	Quantitative analysis model	Simulation model	Integrated model
Implementing			· **Modified AQAL** · **SPATNEX-WE** · TRBNA · CLEWS · PRIMA
Governing	· IAD-NAS · Nexus Assessment 1.0	· **Integrated CGE** · WEF nexus Tool 2.0	· Jordan's framework · **WEAP-LEAP** · WEFO · ZeroNet DSS · MUSIASEM · GCAM-USA
Understanding	· Linkage analysis · MRNN · UWOT · WATER · WESTWeb · REWSS · DEA · **LCA (SimaPro)** · MSA	· **CMDP** · **GLEW** · **WCCEM** · **LCA (SimaPro)**	· Modified SWAT · **RRP** · **TIAM-FR** · Foreseer

Retrieved from Dai et al. (2018). Legend: water-energy (WEN), water-energy-environment nexus (WEEN), water-energy-food nexus (WEFN), water-energy-food-ecosystem nexus (WEFEN), water-energy-land-climate nexus (WELCN).

Understanding the nexus refers to studies that only calculate basic data to demonstrate linkages and identify the key problem, risks, or opportunity areas in water and energy resource management. A study classified as governing the nexus is constructed with the purpose to guide an institutional or policy response towards the problems in resource management. On another hand, implementing the nexus is constructed with the purpose to guide policy and/or technical interventions to improve efficiency or effectiveness of resource uses. Many approaches are at the "understanding" stage of nexus analysis while

fewer approaches are designed to support governance and implementation of technical solutions. Data availability and accessibility is a key challenge and often a key barrier for assessing nexus impacts. Currently, available databases and software make LCA the key tool for integrated nexus assessments (Salmoral and Yan, 2018). The LCA is one of the nexus theme tools most addressed by researchers because of its three resource functions (Torres et al. 2019) and increasingly seen as a key concept for ensuring a transition towards more sustainable production and consumption patterns (Notarnicola et al. 2017). For environmental LCA-based assessment, user-friendly data banks (e.g. Eco invent 3.x, US Life Cycle Inventory Database, Needs LCA, and the ELCD) and LCA modeling tools (e.g. OpenLCA, GaBi, and SimaPro) can be used by LCA practitioners.

2.3 Overview of Life cycle assessment (LCA) methodology

Life cycle assessment (LCA, also known as life-cycle analysis, eco-balance, and cradle-to-grave analysis) is the factual analysis of a product's entire life cycle in terms of sustainability. It accounts for direct and indirect environmental impacts following a "cradle-to-grave" concept, i.e. from materials acquisition to disposal. The LCA is widely used in food production and consumption assessments, water-energy nexus studies, and the context of the WEF nexus from a food perspective (McGrane et al., 2019). The aim of using LCA tools in a nexus study is to draw different environmental impact scenarios to implement sustainable use of water-energy-food resources, thus reducing negative effects on the environment (Mannan et al., 2018). This information can be used with other factors, such as cost and performance data to find optimal solutions for product development, to help in environmental management, and, longer-term, in sustainable development. LCA is a standardized methodology based on ISO 14040/44 standards.

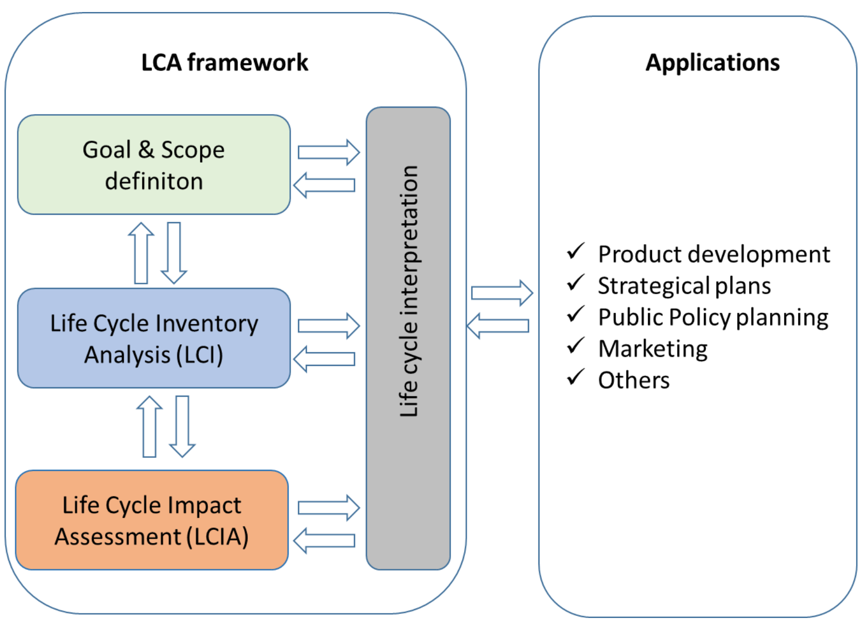


Fig. 3. The basic model of the LCA framework according to ISO 14040/44.

LCA is a standardized methodology based on ISO 14040/44 standards. The LCA methodology consists of four steps: Goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation (Figure 3). The different steps depend on each other.

The first phase of an LCA study consists of defining the goal and the scope of the study where the purpose of the assessment is established and decisions are made about the details of the product system being studied (Curran 2017). The goal definition includes the intended application of the LCA study, purpose, intended audience, and whether to decide if results will be used for comparative analysis (ISO 14045 2012). The scope of the study includes system function (functional unit and reference flow), initial choices (system boundaries, data categories, inputs and outputs, and data quality) and critical review and other procedural aspects. The system boundary (Fig. 4) defines which processes will be included in, or excluded from, the system. LCA can be conducted by assessing the environmental footprint from raw materials to production (Cradle-to-gate) or to be extended to another type of boundary.

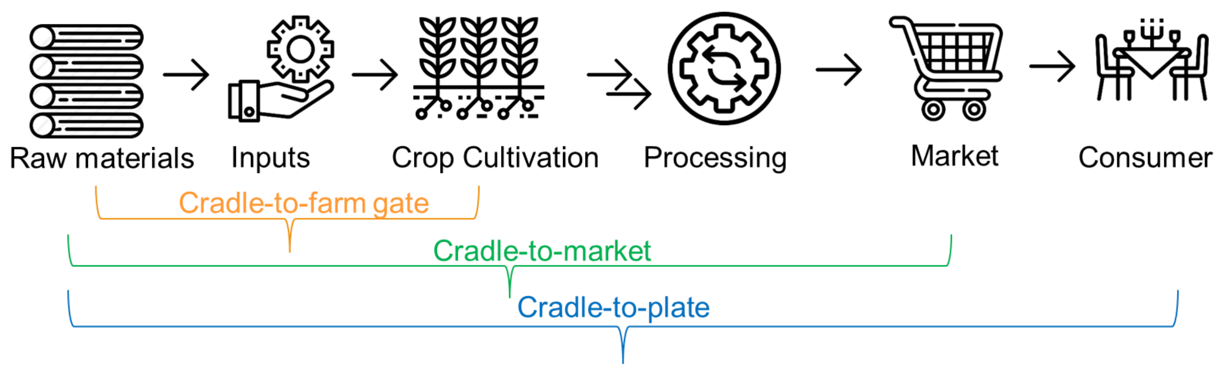


Fig. 4. Examples of system boundaries for Life Cycle Assessment (LCA) of agricultural production.

Normally, a cradle-to-farm gate system boundary is considered for crop production including all upstream processes in resource production (fertilizers, pesticides, electricity, materials) up to the farm-gate where the products leave the farm, i.e., production of farm inputs and on-farm production activities. The functional unit is the quantified definition of the function of a product. It provides a reference for the comparison of two or more products or services delivered to the consumers (ISO 2006). In assessing the efficiency of a production system for a particular crop, the functional unit should be 1 ton of product, whereas 1 hectare should be used in analyzing production intensity (Cerutti et al. 2017). The parallel use of multiple functional units is possible. Once the product system boundary has been set, the resource consumption (inputs) and emissions (outputs) from each unit process connected to the system are compiled creating the so-called life cycle inventory (LCI). Examples are resources, products or by-products, energy, raw materials, emissions, waste, and other releases to the environment (Table 2).

Table 2. The material type is included in the inventory analysis.

Material type	Description
Water	Water service related materials (freshwater, wastewater).
Resources	Various resources (energy, raw materials, chemicals, etc.)
Emissions	Emissions are generated from the processes of both chains and released to the environment.
Products/Services	The main outputs of the water use stage
By-products	Produced by the processes of both chains

Then, in life cycle impact assessment (LCIA) the inventory is analyzed for environmental impact utilizing impact assessment method/s. In LCIA, any flow from LCI contributing to a certain impact category is multiplied by its specific characterization factor to give indicators for the so-called environmental impact categories. The characterization factors represent the potential of a single emission or resource consumption to contribute to the respective impact category. Impact categories (Figure 5) are represented by the corresponding indicators at the midpoint (problem-oriented) and/or at the endpoint level (damage-oriented). Endpoint results are typically shown as an impact on human health, ecosystem quality, and resource depletion (Huijbregts et al. 2017b).

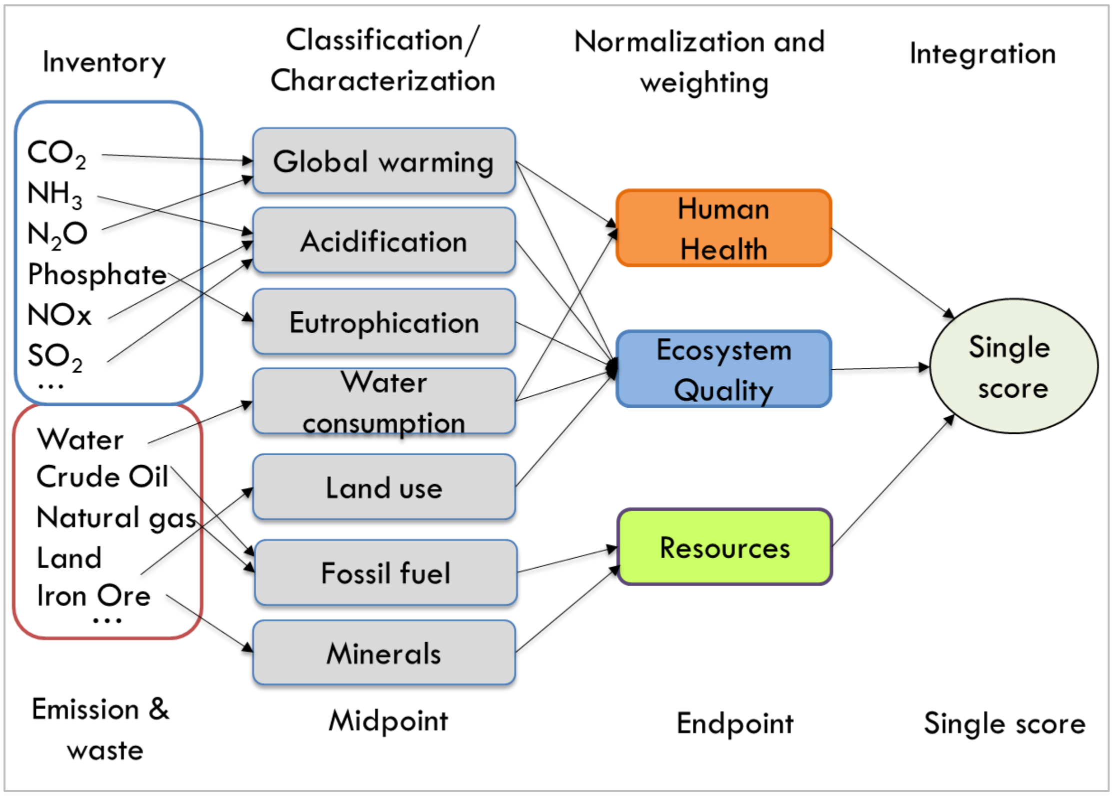


Fig. 5. Procedures for conducting a life cycle impact assessment.

The life cycle impact assessment (LCIA) can be performed by using different methodologies such as CML-IA baseline, Eco-indicator 99, ILCD 2011, and the ReCiPe2016 method. Fig. 5 shows an example of the conversion from emissions to impact potentials via classification and characterization. According to ISO 14044, LCIA proceeds through four steps:

[1] Selection of impact categories and classification (mandatory) - The impact categories are defined and the exchanges from the inventory are assigned to impact categories according to their ability to contribute to different problem areas.

[2] Characterization (mandatory) - The impact of each emission or resource consumption is modeled and calculated quantitatively to common units and finally aggregated within each impact

category, according to the environmental mechanism (see Fig. 6). Together, this results in a numerical indicator result, i.e. the LCIA profile for the product system.

[3] Normalization (optional) – Calculating the magnitude of the category indicator results relative to reference values where the different impact potentials and consumption of resources are expressed on a common scale by relating them to a common reference, to facilitate comparisons across impact categories.

[4] Weighting (optional) – Converting and possibly aggregation of indicators results across impact categories using numerical factors based on value-choices.

The final phase of the LCA evaluates the results of the goal and scope definition, inventory analysis, and impact assessment to select the preferred product, process, or service with a clear understanding of the uncertainty and the assumptions used to generate the results. It is a key aspect to derive robust conclusions and recommendations (Zampori et al. 2016). Still, classic LCA will not determine which product, process, or technology is the most cost-effective or top-performing; therefore, LCA needs to be combined with cost analysis, technical evaluation, and social metrics for comprehensive sustainability analysis (Padilla-Rivera et al. 2019). Moreover, unlike traditional risk assessment, LCA does not necessarily attempt to quantify any specific actual impacts. While seeking to establish a linkage between a system and potential impacts, LCA models are suitable for relative comparisons but maybe not sufficient for absolute predictions of risks. From a nexus perspective, it remains unclear how LCA can be used to analyze the nexus without focusing on any individual sectoral perspective and/or addressing the nexus for a full geographical area since all sectors and activities within the area need to be accounted for. Moreover, existing conventional LCA methods are static and non-spatial being not useful in exploring the nexus in a geographical context (McGrane et al. 2019).

3. Case study 1: A nexus analysis of wastewater reuse.

Adopting an integrated indicator framework (Fig. 6) with life cycle assessment (LCA), environmental life-cycle cost (E-LCC), and Sustainability SWOT (Strengths, Weaknesses, Opportunities, Threats), this work analyzed potential synergies and trade-offs of wastewater reuse in front of a non-reuse scenario in Trinitapoli (Sinistra Ofanto, 41°210 N, 16°030 E; altitude 10 m a.s.l). The focus of this analysis is on the basing/regional scale (Fig. 7) focusing on connections of water, energy, and the environment (WEEN). The data were collected from Consorzio per la Bonifica della Capitanata (CBC) through on-site visits at the irrigation district 17, reports from the literature, and the secondary data sourced from standard life cycle databases. The following sections describe the methodology.

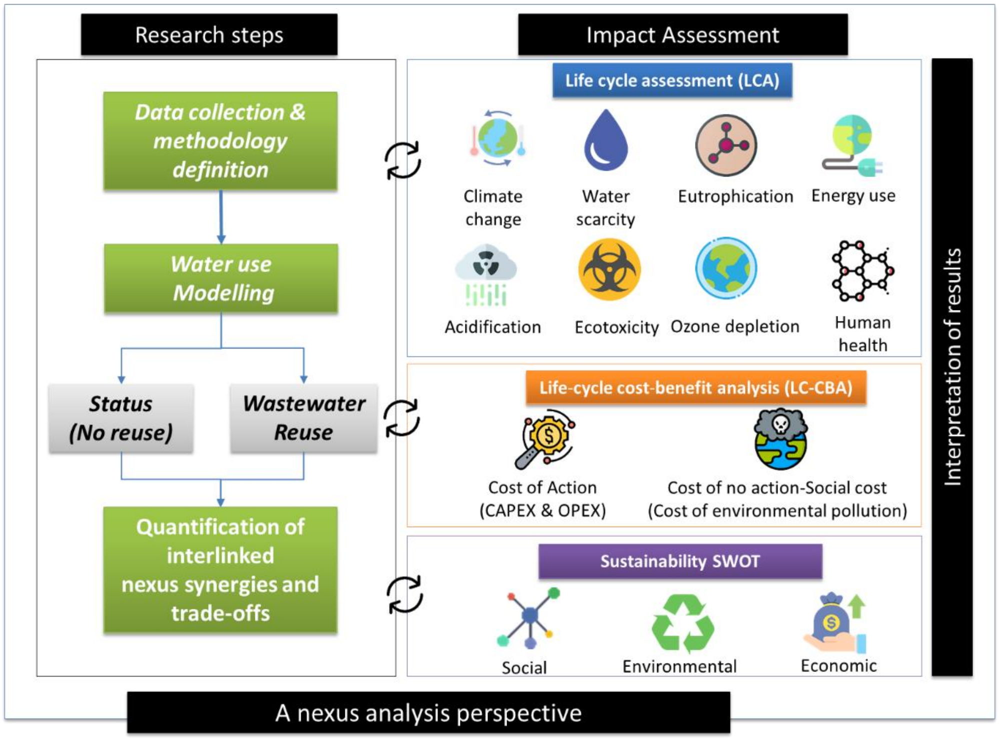


Fig. 6. Life cycle-based nexus framework for the assessment of wastewater reuse in Trinitapoli.

3.1 Case study goal and scope definition

The goal of this nexus-oriented serving as an example for sites with extreme water scarcity is to provide a comparative analysis of crop irrigation strategy with and without water reuse generating useful information about the environmental benefits and drawbacks of different water use options in agricultural fields in Capitanata, Southern Italy. The comparison is based on two scenarios (Fig. 7):

(1) Baseline scenario:(no-reuse): Discharge of wastewater into the sea after secondary treatment and irrigation water supply from groundwater.

(2) Scenario 2 (TWW reuse): Enhanced tertiary treatment (pressurized sand filtration and ultrafiltration) of secondary WWTP effluent to reach Italian standards (M.D 152/2006 and 185/2003) and simultaneously provide tertiary reclaimed water *with certain quality* to agricultural fields.

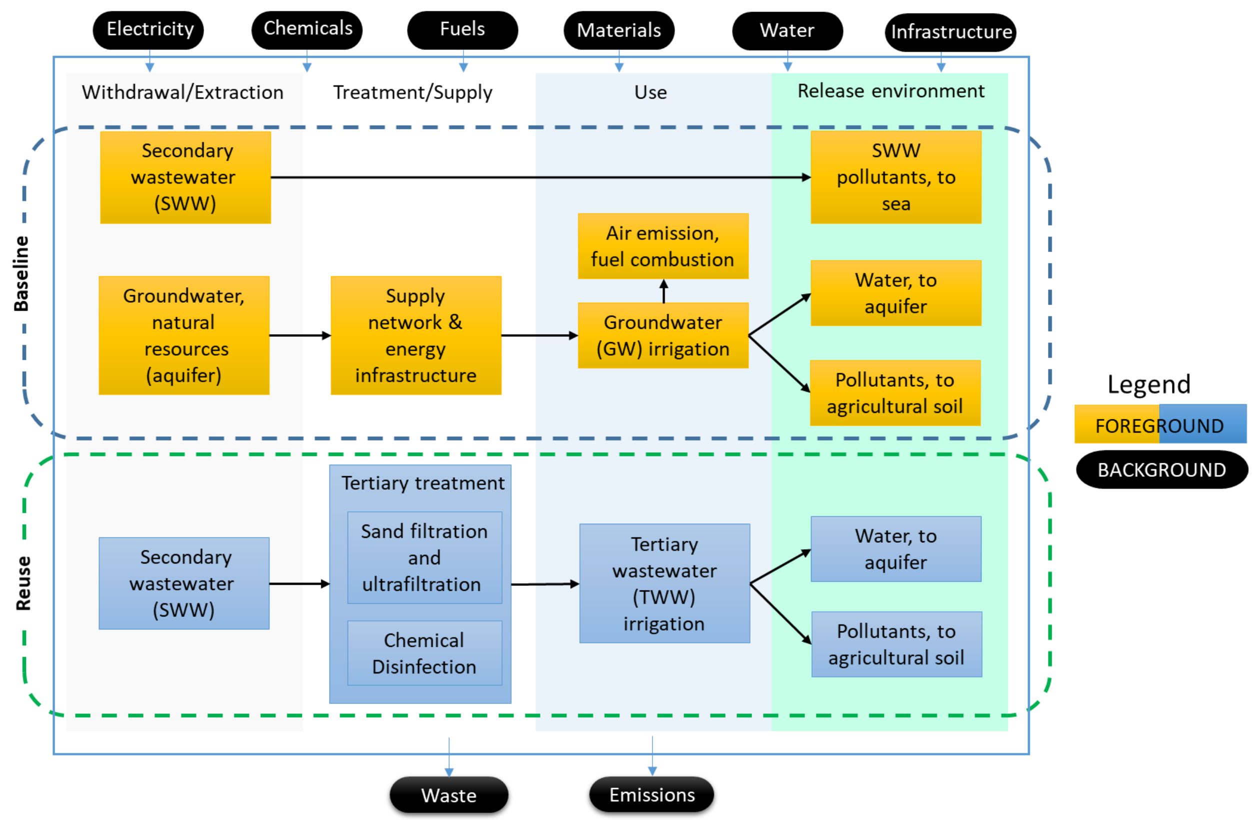


Fig. 7. Overview of system boundaries water-energy-environment analysis of irrigation water use with no-reuse (S1) and reuse (S2).

Fig. 7 shows the system boundaries considered in this study. A series of background process as electricity production, chemicals production, or production and transport of materials for infrastructure were considered. For TWW reuse, the boundaries start from secondary effluent of WWTP and include: i) construction and operation of UF tertiary treatment train, ii) pumping to the field, iii) subsequent release of reused water into the environment through soil runoff, percolation. Primary and secondary wastewater treatment was excluded from the analysis because they remain operational regardless of whether the secondary effluent is used for irrigation or discharged to the sea (Muñoz et al., 2010; Romeiko, 2019). The system function is "Supplying the agriculture production system with supplemental water for crop irrigation including all processes related to this function". For the baseline, both discharges of secondary effluent and water withdrawal/release to natural freshwater resources were included in the assessment, together with materials for the infrastructure. The emission of trace pollutants in wastewater effluent was modeled as disposal to the sea (no-reuse scenario) or agricultural soil (TWW reuse). Credits for irrigation water only accounted for 25% of the volume, as 75% of the water is assumed to be evaporated or incorporated into the plants (Kraus et al., 2013). This loss in irrigation water is relevant for both scenarios. The functional unit (FU) is the 1 m^3 of water of suitable quality for irrigation in agriculture. The volumetric FU is routinely used in most LCA studies. The reference flows are the 1 Mm^3 irrigation water with and without TWW reuse. Table 3 gives a detailed description of the systems studied and assumptions made for this LCA.

Table 3. Details of the systems being studied.

<table>
<tr><th colspan="2">Scenario/Details</th><th>Reuse</th><th>Baseline</th></tr>
<tr><td colspan="2">**The release of water**</td><td>Soil (tertiary effluent)</td><td>Sea (secondary wastewater effluent) + Soil (groundwater)</td></tr>
<tr><td rowspan="2">**System boundaries**</td><td>Starts</td><td>Effluents exit secondary treatment, Including post-treatment and pumping to the field.</td><td>Pumping from the aquifer and pumping to the field.</td></tr>
<tr><td>Ends</td><td colspan="2">Water percolates soil after it was used for irrigation and returns to the environment.</td></tr>
<tr><td colspan="2">**Functional unit**</td><td colspan="2">1 m^3 of water for irrigation in agriculture</td></tr>
<tr><td colspan="2">**Reference flow**</td><td>1 Mm^3 of secondary effluent</td><td>1 Mm^3 of aquifer groundwater</td></tr>
<tr><td colspan="2">**System details**</td><td>333 m^3/h of treated wastewater using the following components (D'Arcangelo, 2006): 5 sand filters (anthracite 1150 kg, quartz sand 4500 kg, and gravel support 2040 kg), 84 ultrafiltration modules with triacetate hollow fiber membranes, a reinforced concrete tank (180 m^3), two horizontal pumps AISI 316 (2 x 11 kW), an air compressor (5.1 kW). The electricity input for UF is 66 kW. A dose of 100 mg sodium hypochlorite (NaClO) is added for each m^3 of water.</td><td>Water supply with 90% diesel and 10% electricity energy. The bore-hole lifetime of 10 years and a pumping depth of 40 m. Typical efficiencies of pumps, electric motors, and diesel engines 66%, 80%, and 45% (Grant et al., 2014; Foley, 2015).</td></tr>
<tr><td colspan="2">**Water withdrawals**</td><td>Accounted as 0.</td><td>Accounted for blue water footprint.</td></tr>
<tr><td colspan="2">**Water releases**</td><td colspan="2">Water release = 25% of the total irrigation volume (Kraus et al. 2013).</td></tr>
<tr><td colspan="2">**Direct air emissions**</td><td>No production of solid waste and atmospheric emissions are expected during the tertiary treatment.</td><td>Airborne emission from diesel combustion in irrigation engines.</td></tr>
<tr><td colspan="2">**Background system**</td><td colspan="2">Production of electricity, chemicals, materials, and infrastructure of each reference system.</td></tr>
</table>

3.2 Life cycle inventory (LCI)

Table 4 summarizes the Life Cycle Inventory (LCI) flows for each scenario, including foreground and background datasets. The inventory list is modeled by choosing the relevant unit flows/processes from the ecoinvent v3.1 database (Ecoinvent Database 3.1, 2014). The data were obtained or measured from high-quality data sources that are specific to the study area. The inventory of TWW reuse represents the full-scale tertiary treatment plant and reuse scheme of Trinitapoli (d'Arcangelo, 2006). The data was provided by local operator Consorzio per la Bonifica della Capitanata (CBC). A design lifetime of 20 years was assumed to normalize the LCI flows.

Table 4. Foreground and background inventory data for 1 m³ of water for irrigation for baseline and wastewater reuse.

Inventory flows	Reuse	Baseline	Unit
Foreground			
Water withdrawal/s from natural resources (Water, well, in ground, IT)	0	1	m³
Water withdrawal/s from technosphere (Reclaimed water from ultrafiltration)*	1	0	m³
Water releases/irrigation and infiltration to natural resources (Water, IT)	0.25	0.25	m³
Discharge of secondary WWTP effluent to the sea*	0	1	m³
Diesel burned in diesel generating set – GLO/IT	0	2.01	MJ
Background			
Market for air compressor, screw-type compressor, 4kW - GLO	3.75E-07	-	Item(s)
Market for electricity, medium voltage – IT	0.586	0.031	kWh
Exhaust air valve production, in-wall housing, plastic/steel, DN 125 - RoW	2.80E-06	2.92E-5	Item(s)
Glass fibre reinforced plastic production, polyamide, injection moulded - RER	5.70E-05	-	kg
Glass fibre reinforced plastic production, polyester resin, hand lay-up - RER	5.70E-05	-	kg
Market for gravel, round - GLO	0.00102	-	kg
Market for hard coal - RoW	5.75E-04	-	kg
Market for polyethylene, high density, granulate - GLO	4.00E-06	-	kg
Market for pump, 40W - GLO	3.75E-04	5.5E-5	item(s)
Market for reinforcing steel - GLO	4.67E-04	1.83E-5	item(s)
Market for sheet rolling, steel - GLO	4.67E-04	1.83E-5	kg
Market for silica sand - GLO	0.00225	-	kg
Ultrafiltration module production, hollow fiber - GLO	1.68E-05	-	kg
Market for sodium hypochlorite, without water, in 15% solution state	1E-04	-	kg
Market for diesel - Europe without Switzerland	-	2.01	MJ

(*) Water includes water quality effects from nutrient and pollutant emissions.

The water quality parameters (Table 5) were retrieved from local experimental work (Gatta et al., 2016; Tarantino et al., 2017). For the baseline scenario, standard calculations supported by local pumping data were used to determine the fuel consumption and infrastructure flows. Typical efficiencies of pumps, electric motors, and diesel engines 66%, 80%, and 45% were considered (Grant et al., 2014). Diesel-combustion emissions were retrieved from the default processes in the ecoinvent database.

Table 5. Main physicochemical parameters of the municipal secondary (SWW), tertiary (TWW) wastewaters, and groundwater (GW) used at Trinitapoli (Apulia region, southern Italy).

Inventory flows	SWW	GW	TWW	Limit 185/03*
pH	7.8 ± 0.1	7.78 ± 0.135	8 ± 0.03	6-9.5
ECw (dS/m)	13.4 ± 0.8	1.42 ± 0.15	1.3 ±9.5	3
TSS (mg/l)	34.6 ± 11.1	3.8 ± 0.85	5.8 ± 1.2	10
Na^+ (mg/l)	126.9 ± 11.2	36.62 ± 1.41	119.6 ± 10.9	-
Ca^{2+} (mg/l)	68.6 ± 2.5	82.33 ± 4.46	67.7 ± 2.3	-
Mg^{2+} (mg/l)	19.6 ± 1.4	10.96 ± 10.96	21 ± 1.5	-
SAR	3.2 ± 0.4	1.3 ± 0.02	3 ± 0.2	10
COD (mg/l)	59.1 ± 8.8	12.03 ± 12.03	35.6 ± 3.57	100
BOD5 (mg/l)	30.7 ± 7.3	7.41 ± 0.63	17.4 ± 2.6	20
NO_3-N (mg/l)	3.8 ± 1.2	23.205 ± 1.22	2.5 ± 0.46	-
NH_4-N (mg/l)	0.2 ± 0.03	0.045 ± 0.005	0.3 ± 0.1	2
Total N (mg/l)	23.5 ± 4.6	26 ± 0.16	19.2 ± 4.4	15 (35)
Phenols (mg/l)	0.7 ± 0.1	-	0.3 ± 0.02	0.1
CO_3^- (mg/l)	340.4 ± 19.4	162.075 ± 3.2	311.6 ± 9.9	
HCO_3^- (mg/l)	528.2 ± 33.8	245.6 ± 5.99	459 ± 15.5	
PO_4-P (mg/l)	6.2 ± 0.4	0.105 ± 0.01	7.3 ± 0.75	10 (2)
K^+ (mg/l)	22.6 ± 4.7	11.96 ± 1.64	22.8 ± 4.8	
Sulfates (mg/l)	86.3 ± 8.7	30.66 ± 1.93	85 ± 8.9	500
Chlorides (mg/l)	438.7 ± 137.1	18.82 ± 9.33	375.1 ± 110.38	250
Fluorides (mg/l)	0.4 ± 0.05	0.6 ± 0.01	0.4 ± 0.03	1.5

* Limit concentration for total nitrogen and total phosphorus (in brackets the limit concentration for vulnerable areas to nitrate and phosphate)

3.3 Characterization of nexus profile

The redeveloped and updated ReCiPe 2016 (hierarchist perspective) one of the latest impact assessment methods was applied to calculate 21 harmonized impact scores (Table 6). ReCiPe 2016 model comprises 18 midpoint impact categories and 3 endpoint impact categories The results were further aggregated into a single one dimensionless single indicator (a so-called single score) after applying normalization and weighting (World ReCiPe H/H), which can be useful for a comparative LCA study. The normalization and weighting factors were retrieved from SimaPro 8.0.3 implementation as indicated by the method developers. The environmental impacts were quantified in monetary terms using the Environmental Prices method (De Bruyn et al., 2018). The cost refers to the social cost of pollution (welfare costs) expressing the price that society is willing to pay for less environmental pollution or to produce more sustainably (De Bruyn et al., 2018). The assessment was made midpoint level (per impact category). The midpoint-level prices as external cost (Table S1, Supplementary Information) were used for assessment. Environmental Prices does not assign values for resource consumption (fossil fuels, metals, water), because the market price of these resources already reflects scarcity considerations to a certain extent. Like in LCA, the environmental LCC is a steady-state model, and therefore no discounting of the results is usually performed (Rödger et al. 2017). Impact calculation was carried out using OpenLCA 1.10.2 (GreenDelta 2014) with the LCIA method pack v2.1. Secondary datasets from the Ecoinvent v3.1 database (Ecoinvent, 2016) were used to model the background environmental impact.

Table 6. ReCiPe 2016 impact categories, the connection between midpoint and endpoint categories, and normalization and weighting set.

Midpoint impact category	Endpoint impact category			Available Country-specific impacts	Global normalization factor*
	Damage to Human health	Damage to Ecosystems	Damage to Resource availability		
Global warming	+	+			0.000152
Stratospheric ozone depletion	+				16.7
Ionizing radiation	+				0.00208
Human health ozone formation	+			+	0.0486
Fine particulate matter formation	+			+	0.0391
Ecosystem Ozone Formation		+		+	0.0563
Terrestrial acidification		+		+	0.0244
Freshwater eutrophication		+		+	1.54
Marine eutrophication		+			0.217
Terrestrial ecotoxicity		+			0.000965
Freshwater ecotoxicity		+			0.815
Marine ecotoxicity		+			0.969
Human carcinogenic toxicity	+				0.361
Human non-carcinogenic toxicity	+				0.00671
Land use		+			0.000162
Mineral resource scarcity			+		0.00000833
Fossil resource scarcity			+		0.00102
Water consumption	+	+		+	0.00375
Normalization factor*	42.1	1396	0.0000357		
Weighting factor*	400	400	200		

3.4 Nexus results

3.4.1 Nexus synergies and trade-offs at midpoint level

Table 7 presents the quantified midpoint life cycle environmental impacts of water reuse and the no-reuse. Negative values indicate environmental benefits while positive values mean damages to the environment. The water reuse shows particular advantages in its environmental profile in terms of impact categories depending on direct emissions i.e. water consumption, nitrogen-based marine eutrophication, particulate matter formation, and ozone formation. As a non-natural resource, wastewater has no withdrawal impact allowing a net saving of water from nature. Other authors (Arzate et al. 2019; Kraus et al. 2013; Pintilie et al. 2016) have reached similar conclusions about the benefits of water-use related environmental impacts. The indirect effects of water reclamation on total water consumption are marginal compared to the direct effects of water reuse confirming similar conclusions reached by Kraus et al. (2013). Eutrophication is the relevant impact category in wastewater systems which is dominated by nutrient emissions in effluents (Munoz et al., 2009). Thus, nutrient content variability in influent and the related effluent will affect their performance and directly influences the amount of fertilizer that can be replaced in agricultural applications (Meneses et al. 2010). The water reuse reduces nitrogen-related emission discharge into the sea delivering a significant benefit on marine eutrophication, however, it does not reduce freshwater eutrophication because tertiary effluent is still high in nutrients. Tertiary treatment

will directly transfer effluent N and P to irrigated fields and a small fraction of total phosphorus and nitrogen could eventually be transferred with irrigation water via soil and groundwater into surface or marine environments (Kraus et al. 2013). However, because most of these nutrients are absorbed by the crop they are removed from the water cycle reducing the use of additional fertilizers (benefits for the environment, farmers, and wastewater treatment) and hence play no further role in the eutrophication in the eutrophication of rivers and the creation of dead zones in coastal areas (FAO 2002). The latter is one of the most severe and widespread causes of marine ecosystem disturbance (Huijbregts et al. 2017a).

Table 7. Life-cycle midpoint environmental impacts of reuse versus no reuse (baseline) for crop irrigation. Highlighted cells correspond to better performance.

Impact category	Unit	Baseline	Reuse
Fine particulate matter formation	kg PM2.5 eq	1.35E-03	6.77E-04
Fossil resource scarcity	kg oil-eq	0.09	0.12
Freshwater eco-toxicity	kg 1,4-DCB-eq	1.48E-03	7.58E-03
Freshwater eutrophication	kg P-eq	9.57E-04	1.14E-03
Global warming	kg CO_2-eq	0.28	0.41
Human carcinogenic toxicity	kg 1,4-DCB-eq	5.02E-03	8.71E-03
Human non-carcinogenic toxicity	kg 1,4-DCB-eq	4.04E-02	1.60E-01
Ionizing radiation	kBq Co-60-eq	8.43E-03	6.68E-02
Land use	m^2a crop-eq	1.07E-03	7.14E-03
Marine eco-toxicity	kg 1,4-DCB-eq	2.33E-03	1.03E-02
Marine eutrophication	kg N-eq	2.73E-02	3.18E-03
Mineral resource scarcity	kg Cu-eq	0.001	1.55E-03
Ozone formation, Human health	kg NOx-eq	3.57E-03	8.60E-04
Ozone formation, Terrestrial ecosystems	kg NOx-eq	8.27E-03	1.99E-03
Stratospheric ozone depletion	kg CFC11-eq	1.59E-07	2.40E-07
Terrestrial acidification	kg SO_2-eq	2.60E-03	2.04E-03
Terrestrial eco-toxicity	kg 1,4-DCB-eq	2.81E-01	6.30E-01
Water consumption	m^3 consumed	0.38	-0.18

Fine particulate matter and ozone formation were mainly influenced by lower emissions to air, like ammonia (NH_3), particulate matter (PM2.5), sulfur dioxide (SO_2), and nitrogen oxides (NO_x). Despite the local benefits, TWW reuse increases several other midpoint-based environmental impacts from additional efforts for water reclamation. Electricity (grid mix) represents the largest contribution to the majority of impacts since it contains a higher percentage of natural gas. Infrastructure-related impacts were more noticeable for mineral resources and toxicity-related indicators, and land occupation. Electricity consumption is an operational element that delivers a continuous contribution to the impact on the environment as long as the treatment systems are used (Al-Sarkal and Arafat, 2013). It typically defines the environmental impacts of wastewater treatment (Moretti et al., 2019). Infrastructure poses a one-time impact associated and has only a minor impact on the overall environmental profile due to the long life of the equipment used in associated processes (Seis and Remy, 2013).

From the characterized results it can be concluded that water reuse has particular advantages in its environmental profile in terms of water consumption and eutrophication-based impact categories. The water consumption is mainly influenced by the volume of groundwater withdrawal (and release) for agricultural irrigation because as a non-natural resource, wastewater has no impact. For other impact categories (e.g. land use, human toxicity, eco-toxicities), the performance of reuse is strongly influenced by the background processes. It should be highlighted that groundwater-table-depth, the energy efficiency of pumps, and the type of energy used will lead to different levels of energy consumption which can make the environmental profile of the two scenarios similar or different.

3.4.2 Nexus synergies and trade-offs at the endpoint level

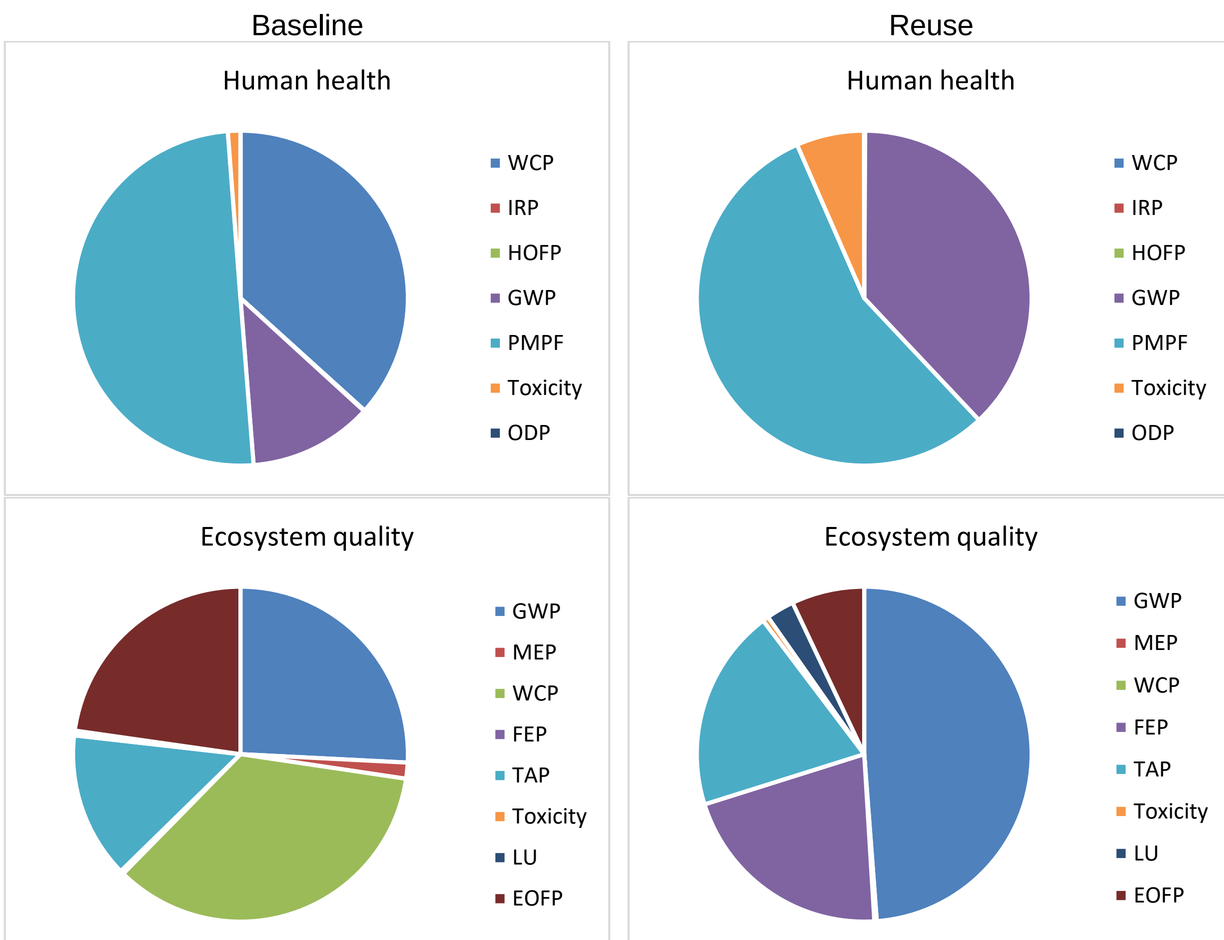
To facilitate the comparison in the impact assessment and interpretation, 18 midpoints were converted to 3 easy, but more uncertain endpoint impacts (Table 8). This simplifies LCA results since a large number of midpoint indicators are very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning (Huijbregts et al. 2017b).

Table 8. LCA endpoint impact scores for baseline (no-reuse) and reuse. The importance of the impacts is shown through the color code from red = highest impacts to green = lowest impacts.

Impact categories	Baseline	Reuse	Unit/m^3
Damage to human health			
Water consumption, Human health	7.89E-07	-3.85E-07	DALY
Ionizing radiation	7.15E-11	5.67E-10	DALY
Ozone formation, Human health	1.47E-09	3.57E-10	DALY
Global warming, Human health	2.57E-07	3.79E-07	DALY
Fine particulate matter formation	1.08E-06	5.54E-07	DALY
Human carcinogenic toxicity	1.67E-08	2.89E-08	DALY
Stratospheric ozone depletion	8.42E-11	1.28E-10	DALY
Human non - carcinogenic toxicity	9.22E-09	3.66E-08	DALY
Damage to ecosystem quality			
Global warming, Freshwater ecosystems	2.12E-14	3.12E-14	species.yr
Marine eutrophication	4.65E-11	5.42E-12	species.yr
Land use	9.38E-12	6.33E-11	species.yr
Water consumption, Aquatic ecosystems	8.26E-14	-3.87E-14	species.yr
Marine ecotoxicity	2.46E-13	1.09E-12	species.yr
Water consumption, Terrestrial ecosystem	1.05E-09	-4.69E-10	species.yr
Global warming, Terrestrial ecosystems	7.77E-10	1.14E-09	species.yr
Freshwater ecotoxicity	1.04E-12	5.25E-12	species.yr
Ozone formation, Terrestrial ecosystems	6.85E-10	1.65E-10	species.yr
Terrestrial acidification	4.25E-10	4.57E-10	species.yr
Freshwater eutrophication	1.01E-11	4.94E-10	species.yr
Terrestrial ecotoxicity	3.21E-12	7.19E-12	species.yr
Damage to resources			
Mineral resource scarcity	1.85E-04	6.14E-07	USD2013
Fossil resource scarcity	3.89E-02	1.87E-09	USD2013

Endpoints are defined as the final damage to the natural environment (biodiversity), human health, and raw material exhaustion, which are caused by the various environmental effects at the midpoint level. At

the endpoint level, The TWW shows higher advantages in all three endpoints. Reuse is more impactful for global impact categories directly affected by background processes while the non-reuse is dominated by the local impacts of marine eutrophication (nutrient emissions into the environment) and water consumption (water from natural resources). For reuse, the damage to human health is caused by emissions leading to particulate matter formation and global warming (Fig. 8). The damage to ecosystems is caused by emissions leading to global warming, terrestrial acidification, and freshwater eutrophication. Overall, reuse results in lower damage to resources because fossil resource scarcity does not have a constant mid-to-endpoint factor and the damage is calculated based on individual factors for each substance (crude oil, hard coal, lignite, natural gas).



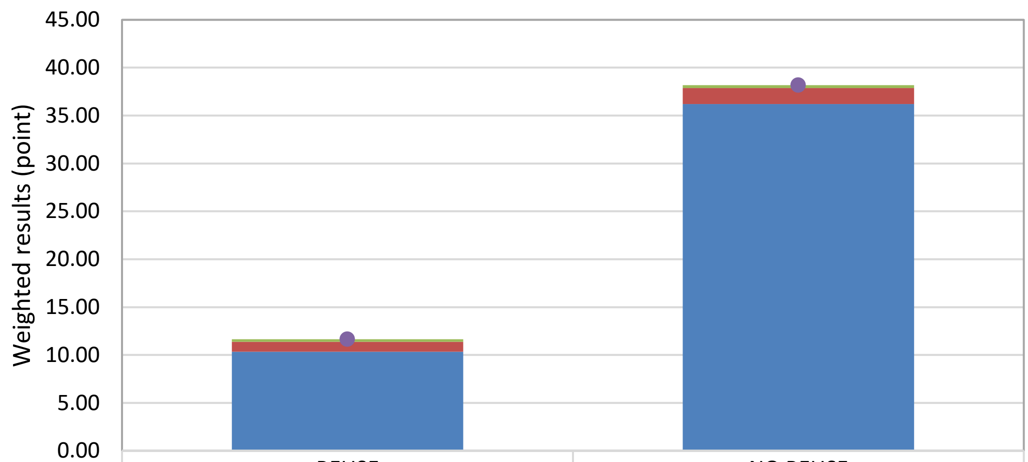
Legend: GWP: global warming potential; ODP: ozone depletion potential; PMFP: particulate matter formation potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; TAP: terrestrial acidification potential; WCP: water consumption potential; LU: Land use; IRP: ionizing radiation potential]

Fig. 8. Share of the impact of midpoint indicators on endpoint indicators for no-reuse and reuse.

3.4.3 Single score WEEN nexus impact

The endpoint impact scores were aggregated into single score results following normalization and weighting (Fig. 9) giving different weights to the different environmental impacts to enable the

comparison of overall expected environmental impacts using reference numerical scores (Sala et al. 2018). The single score result indicates that reuse has the lowest damaging environmental score with 11.66 points versus 38.17 points of the baseline. The avoided impacts of water withdrawal and related impacts on human health give the highest environmental gain a single score. Analyzing trade-offs between foreground and background contributions, implementation of tertiary treatment leads to a shift in environmental impacts, reducing direct or "local" emissions at the agriculture site (water discharge in the sea and local pollution from diesel production/combustion impacts) and increasing indirect or "global" emissions from the supply of electricity, chemicals, and infrastructure. From endpoint indicators and weighted results expressing LCA results in an aggregated manner, it can be concluded that reuse can supply additional water without increasing local water scarcity thereby producing an overall lower single score value of LCA results. In both cases, over 70% of final damage originated from human health impacts.



	REUSE	NO REUSE
Resources (pt)	0.27	0.28
Ecosystems (pt)	1.05	1.68
Human Health (pt)	10.34	36.21
Single Score (pt)	11.66	38.17

Fig. 9. Weighted results (ReCiPe 2016), showing a single environmental impact score for reuse and no-reuse.

3.4.4 Cost of pollution – Environmental costs

The results of the cost analysis including environmental (external) and reclamation (internal) costs are summarized in Fig. 10. The environmental cost of the TWW reuse and the no-reuse are 0.064 €/m^3 and 0.175 €/m^3 respectively. The overall costs (reclamation+ environmental) was estimated at 0.59 €/m^3 and 0.55 €/m^3 for baseline and water reuse, respectively. Although the reuse has a higher internal cost profile, results show that wastewater reuse is feasible from an economic point of view if external costs are integrated into the overall economic assessment. The external costs using the Environmental Prices Handbook EU28 version (De Bruyn et al., 2018) were estimated at 0.175 €/m^3 and 0.064 €/m^3 for reuse and non-reuse option, respectively. In other words, if reuse is unimplemented, 0.175 €/m^3 are generated

as external costs or potential environmental benefits are lost. This means social non-market benefits would already justify the implementation reuse in economic terms (Alcon et al., 2013) and confirm Hernández-Sancho et al. (2015) that integrating only internal costs subtly undermines the economic feasibility of many water reuse projects.

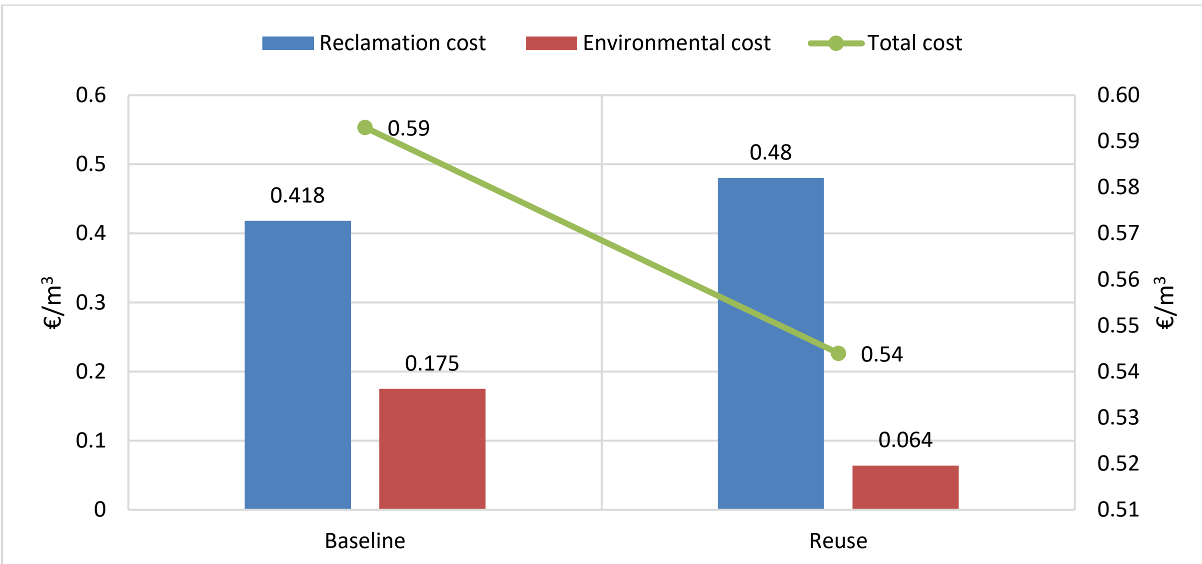


Fig. 10. Environmental (external) and conventional (internal) costs for reuse and no-reuse using a life cycle perspective.

The most enormous environmental benefit for reuse is the prevention of nitrogen-based emissions in water bodies leading to a reduction of marine eutrophication which induces 67.2% of the external cost for no-reuse (Fig. 11).

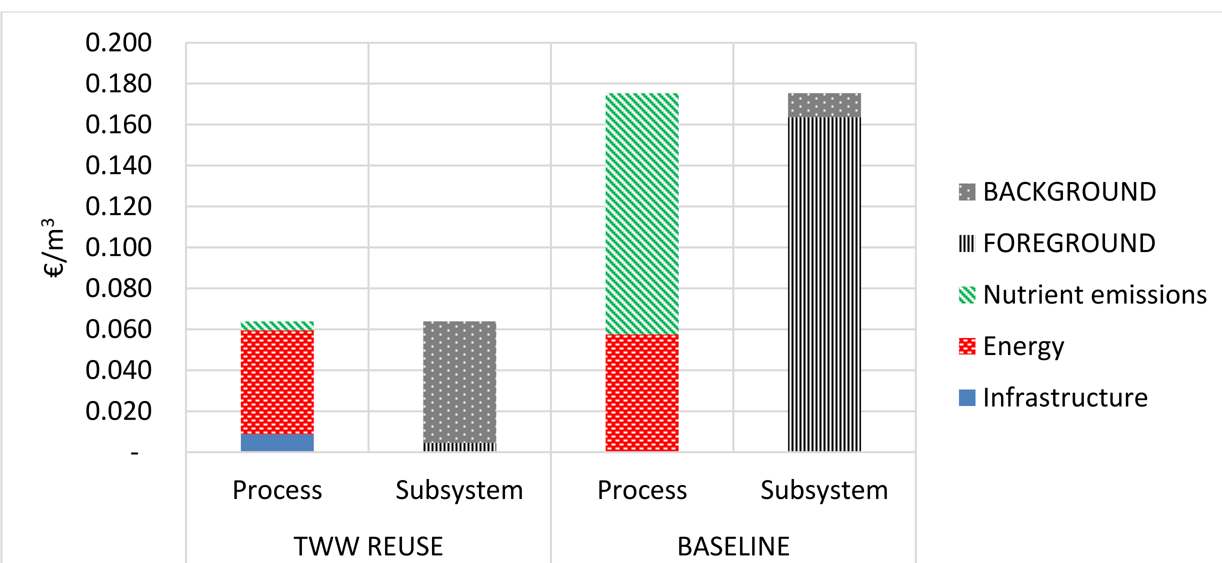
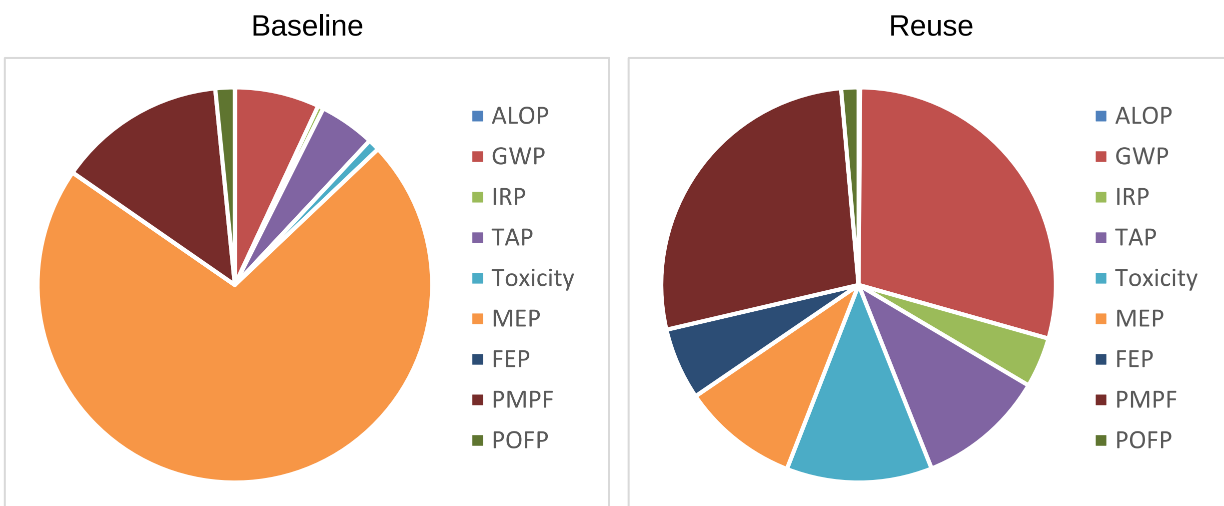


Fig. 11. Analysis of environmental life cycle costs at the process and sub-systems level.

On another hand, tertiary treatment schemes will increase energy demand and related emissions affecting global environmental impacts. Background processes produced 92.9% of the external cost with TWW reuse. Electricity was the main contributor representing 79.3% of the external cost. They are directly related to global warming (29%), fine particulate matter formation (27%), and terrestrial acidification (10%) impact categories arising from electricity, chemicals, and infrastructure (Fig. 12). On other hand, the most enormous socio-economic benefit for TWW reuse is the prevention of nitrogen-based emissions linked to marine eutrophication which induces more than 65% of the external cost for baseline (Fig. 12).



Legend: GWP: global warming potential; ODP: ozone depletion potential; PMFP: particulate matter formation potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; TAP: terrestrial acidification potential; WCP: water consumption potential; LU: Land use; IRP: ionizing radiation potential.

Fig. 12. Analysis of environmental life cycle costs per midpoint impact category.

3.4.5 SWOT analysis of wastewater reuse benefits and trade-offs

To summarize the most important sustainability aspects we drafted a Sustainability SWOT (Strengths, Weaknesses, Opportunities, Threats) presented in Table 9 combining basic SWOT and water-energy-pollution dimensions. The multi-impact LCA analysis illustrated that a general conclusion from the environmental assessment is difficult to draw. Analyzing trade-offs between global and local effects indicates that water reuse overcomes the local water scarcity the main factor limiting agricultural productivity in the region. This will lead to improved local water availability by 1 Mm^3, increase the potentially irrigable area by 500 ha considering net water supply to the agricultural area 2000 m^3/ha, mitigate competition between cities and agriculture for water, combating salinization markedly noticed in Trinitapoli, and increasing competitiveness and stimulating innovation. Treated agro-industrial wastewater in irrigation in Southern Italy could save about 6000 m^3/ha of groundwater every year (Libutti et al. 2018) translated into significant cost savings (>2220 €/ha). The intensive agriculture has altered the balance of the underground aquifers with many areas vulnerable to salt contamination (2 gr/l) thus making reuse indispensable for ensuring the long-term sustainability of agricultural production. The

"new" freshwater" without increasing local water scarcity and nutrient loads to receiving surface waters trigger net environmental (e.g. water consumption potential) and health-related benefits (e.g. less emission from water deprivation and degradation, thus, less cumulative impacts on local human health and ecosystem quality) conditions. The average benefit (economic value of water as a productive factor) derived from irrigation wastewater amounts to 0.21 €/m^3 with an annual average volume of 2475 m^3/ha (Arborea et al. 2017). The shift from pumped groundwater to reclaimed water for irrigation can save also pumping costs up to 20-25 €/hour or 0.37 to 0.465 €/m^3 (Fatone 2017).

Table 9. SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of wastewater as an option additional water supply.

	Helpful to achieving the objective	**Harmful** to achieving the objective
Internal origin (attributes of the system)	***Strengths*** • Climate-resilient source of water with good quality. • Improving water scarcity conditions. • Less downstream nutrient-related pollution. • Desertification control (prevention of land erosion). • Maintain crop yields and income generation. • Increased competitiveness and stimulate innovation. • Value of nutrients for irrigation. • Existing infrastructure with an advanced tertiary system for water treatment.	***Weaknesses*** • Energy-related environmental impacts for treatment. • Not optimized based on life cycle thinking. • Restrictive legislation and poor-coordination. • Lack of operational experience.
External origin (attributes of the environment)	***Opportunities*** • Energy-saving measures and technologies. • Preserving groundwater resources and their related environmental impacts. • Reduces the risks to the environment and human health by unplanned reuse. • Adaptation to climate change. • Communication and awareness-raising campaign. • High acceptance among stakeholders and farmers. • Reduced water cost. • Reduce the cost of pollution.	***Threats*** • Insufficient water supply. • Variability of the WW characteristics. • Perception of build-up chemical pollution in the soil. • Health risks for farmers. • Resource availability. • Marketability of crops. • Public perception of reduced quality.

The use of reclaimed wastewater for irrigation undoubtedly has significant non-market environmental benefits (preservation of the ecological status of the river basin and social side effects of employment in agriculture) which lead to better informed and more efficient water management decisions (Alcon et al. 2013). Water scarcity is at present having economic repercussions in terms of local employment and contribution to economic development with about 73 agro-companies are closed every year in the area of Barletta-Trani located close to Trinitapoli (Fatone 2017). This leads to the local unemployment of 8 workers (5 males and 3 females) and loss of income of nearly 4670 €/ha.

TWW irrigation can be as profitable as, and sometimes better than, freshwater irrigation. The crop yields in field experiments in Southern Italy obtained with treated wastewater were generally higher than those obtained with freshwater (Bedbabis et al. 2015; Campi et al. 2016; Cirelli et al. 2012; Gatta et al. 2015). The multi-year demonstration activities in Southern Italy for irrigation of olives (Palese et al. 2009), vegetable crops (Lonigro et al. 2016), tomato, and broccoli (Vergine et al. 2017) have shown no negative effects on soil salinity and microbial safety of crops therefore with no or limited risks for human health. Moreover, previous experimental analysis in the study area demonstrated that the tertiary effluent has better characteristics than underground waters with no presence of any dangerous pollutant, like pesticides, solvents, and heavy metals, thus, causing no pollution or degradation neither of the soil nor groundwater (D'Arcangelo 2005). Still, the concept of "zero risks" in agricultural production is achieved using certain technological options that fulfill the objective of agricultural reuse (Jaramillo and Restrepo 2017). This includes high-tech wastewater treatment, crop selection and restriction, wastewater irrigation techniques, and human exposure control (Carr 2005). It is demonstrated that the drip irrigation system avoids close contact between water and plant, contributing to decreasing Fecal coliforms and Total heterotrophic count in plant and crop products (Libutti et al. 2018).

Farmers of Apulia and more generally, of the Mediterranean territories are undoubtedly living water scarcity and negative impacts of groundwater over-exploitation as a daily challenge. Strong opportunities drive the reuse through resilient agriculture systems, better environmental performance from water consumption, local jobs, and collaboration between stakeholders. These benefits are not offset by marginal upstream (global) environmental impacts of energy-intensive for water treatment and costly operations. Stakeholders should implement reuse while investing a reasonable amount of effort and financial resources on engineering solutions on WWTP premises (e.g. solar panels to avoid the use of fossil fuels) for improving environmental performance. On the economic side, the expected market and non-market benefits of using reclaimed wastewater for agriculture justify its implementation, as they significantly overcome the average treatment costs. Farmers are not committed to contribute to the cost of water reclamation (pay the only delivery cost of 0.12 €/m^3) an offsetting element for adoption irrigation reuse since in many cases cost recovery from the farmers is unlikely to be feasible.

Social awareness and concern about the risks to public health are the keys to the success of wastewater reuse in the Mediterranean region (Baghapour et al. 2016; Hettiarachchi and Ardakanian 2018). The question of the social acceptability of using treated wastewater in irrigation relates to how receptive farmers and consumers will be to the process and the resulting product quality (Mizyed 2013). Social acceptance of wastewater reuse is affected by lack of coordination between the authorities involved in planning; inadequate community consultation; lack of trust in the technology; social pressure and fear of social backlash; and fear of losing markets in case of wastewater reuse in irrigation (Saad et al. 2017). Depending on public perceptions, impressions, and attitudes, the development of a wastewater scheme can be supported or constrained (Saad et al., 2017). In Southern Italy, the public is more enthusiastic about reuse than farmers as demonstrated by Saliba et al. (2018) where the level of acceptance of wastewater reuse was found 59 and 87% for farmers and citizens/consumers, respectively. To overcome the problem of social acceptability and public information the education, public information campaigns, and training programs for farmers and people from all community levels, can be introduced including technical, environmental, health, and socio-economic aspects. The continuous exchange of information

ensures better outcomes in terms of health safeguards, environmentally sound practices, or basic agronomic and on-farm principles.

4. Case study 2: WEEN nexus index analysis of irrigated district/s

In this case study, the objective is to analyze the water-energy-food-environment nexus of the crop production system and explore the role of irrigation in the nexus performance. The study case is the irrigation district (District 1-a) in the 'Sinistra Ofanto' irrigation scheme. It covers a total area of 660 ha (564 ha irrigable land) and a total irrigated area of 211.6 ha. District 1-a is equipped with an upstream pumping station, it is designed for on-demand operation with an upstream peak discharge of 185 l/s. The district is divided into 8 sectors (Figure 12), each composed of several farms served by 74 hydrants, and all have a module of 10 l/s. All the farms are equipped with drip irrigation methods. The distribution of water for irrigation use in the districts, as a rule, begins on March 1st and ends November 30th of each year. The main irrigated crops being tomatoes (35%) and asparagus (30%).

Fig. 13. The layout of District 1-a and associated districts.

4.1 Nexus modeling using LCA

Figure 14 illustrates the generic system boundaries used in this study following a cradle-to-farm-gate approach. Agriculture uses direct and indirect energy. Hence, emissions and impact on the environment were categorized into direct (foreground) and indirect (background). Background datasets include emissions resulting from the production of water, electricity, fertilizer, pesticides, diesel, and agricultural machinery. Foreground datasets contain emissions due to the combustion of fossil fuels by the tractor and application and emissions of fertilizers and pesticides in the soil. All energy consumption, material use, and associated emissions were allocated 100% to the crops since the crops are the only product of

the irrigation scheme (Naderi et al., 2019). The environmental impacts on a cluster level are calculated based on the water supply to crops and corresponding agronomic practices using a mass-based and area-based functional. The cultivation area (1 ha) was adopted as the main functional unit. This parameter represents the impact intensity of a crop/farm/irrigation scheme. The performance was further studied using a mass-based functional unit of 1 ton of final product. This represents farm technical efficiency and the nexus footprint of each crop.

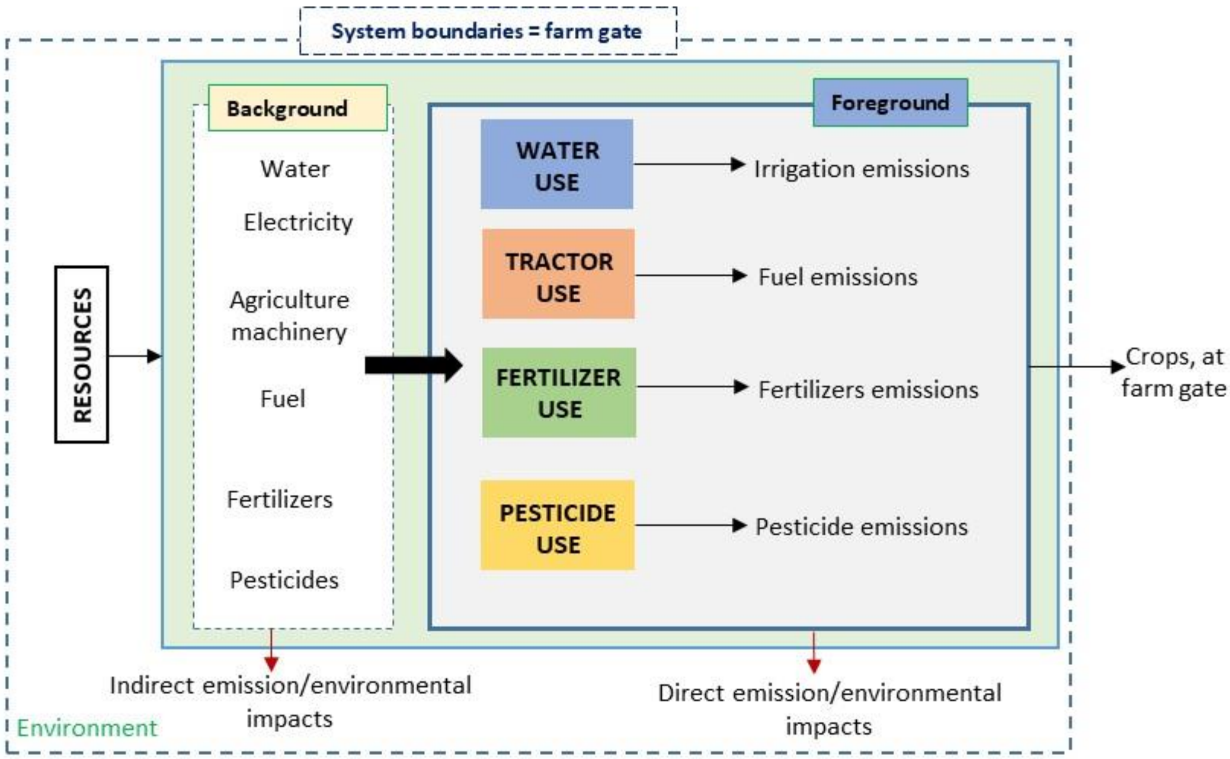


Fig. 14. System boundary and included processes in nexus performance.

The input and output flow for each crop are presented in Table 10. The data were collected from CBC through an informal interview, and the secondary data sourced from standard life cycle databases. Field emissions were estimated using specific models and guidelines: IPCC guidelines (2006) for fertilizer use and N related emissions, Nemecek and Kagi (2007) for phosphorus and diesel combustion-related emissions, Ecoinvent Database 3.1 (2014) for pesticide emissions. For N-related emissions, ammonia (NH_3), nitrous oxide (N_2O), and nitrogen oxide (NOx) emissions to air and nitrate (NO_3-) leaching losses were included in the model assessment. Stock changes in soil organic carbon (SOC) were not accounted for due to a lack of specific data. LCA-based Cumulative Energy Demand (energy consumption), and environmental Prices were applied to enhance understanding of resource use and emission-based impacts.

Table 10. Input and output flow for crop production in district 1-a, Sinistra Ofanto.

Crop	Tomato	Asparagus	Olives	Apple	Grapevine	Pepper	Peach	Artichoke	Watermelon	Cherry
Yield (ton/ha)	93.1	10	7	20.5	30	25	40	10	65	10
Area (ha)	74.5	62.2	21.5	14.6	11.5	6.6	5.6	4.3	4.1	1.1
GIR (mm/ha)	568	384	271	476	362.5	409	516	285	464.6	582
Irrigation percentage	0.75	0.80	0.32	0.90	0.90	0.88	0.93	0.72	0.83	0.93
Electricity(kWh/ha)	1052	759	214	1058	806	889	1185	507	952	1337
Nitrogen (kg/ha)	150	120	100	130	100	150	150	200	120	100
Phosphate (kg/ha)	100	80	80	80	100	100	120	120	100	80
Potassium (kg/ha)	150	80	120	150	100	150	120	100	100	100
Pesticides (kg/ha)	5	6	2	8	4	5	3	5	3	7
Diesel fuel (kg/ha)	50	50	37.5	15	62.5	60	37.5	100	62.5	45
Tractor module (kg/ha)	5	6	3.5	7.5	6	6	3.50	7.50	5	5
Soil N_2O (kg/ha)	3.13	2.5	2.08	2.7	2.08	3.13	3.13	4.16	2.5	2.08
Ammonia (NH_3) (kg/ha)	18.21	14.57	12.14	15.78	12.14	18.21	18.21	24.28	14.57	12.14
Nitrogen oxides (kg/ha)	0.50	0.40	0.33	0.43	0.33	0.50	0.50	0.66	0.40	0.33
Nitrates (kg/ha)	199.16	159.3	132.7	172.6	132.7	199.1	199.1	265.54	159.3	132.7
Phosphorus (kg/ha)	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Phosphates (kg/ha)	1.32	1.28	1.28	1.28	1.32	1.32	1.36	1.36	1.32	1.28

4.2 Cumulative energy and water demand

The cumulative energy and water demand for each crop are shown in Fig. 15 and Fig. 16. The average CED of irrigation district 1-a is 24,766 MJ-eq/ha or 877 MJ-eq/kg. When looking at the CED and water footprint for 1 ha, fruit, apple, and peach hold the first places because they need more irrigation water. On the other hand, olives have the lowest CED and water demand. According to the results for 1 ton, the highest CED and water is related to Artichoke production while the lowest for tomatoes. The CED required for these crops are determined to be 337 and 2929 MJ/ton, respectively. The water required for these crops is determined to be 1758 kg and 14993 kg/ton, respectively. The analysis indicates that notwithstanding greater application rates for water and nitrogen fertilizers that more efficient systems (high yielding) have a lower environmental impact.

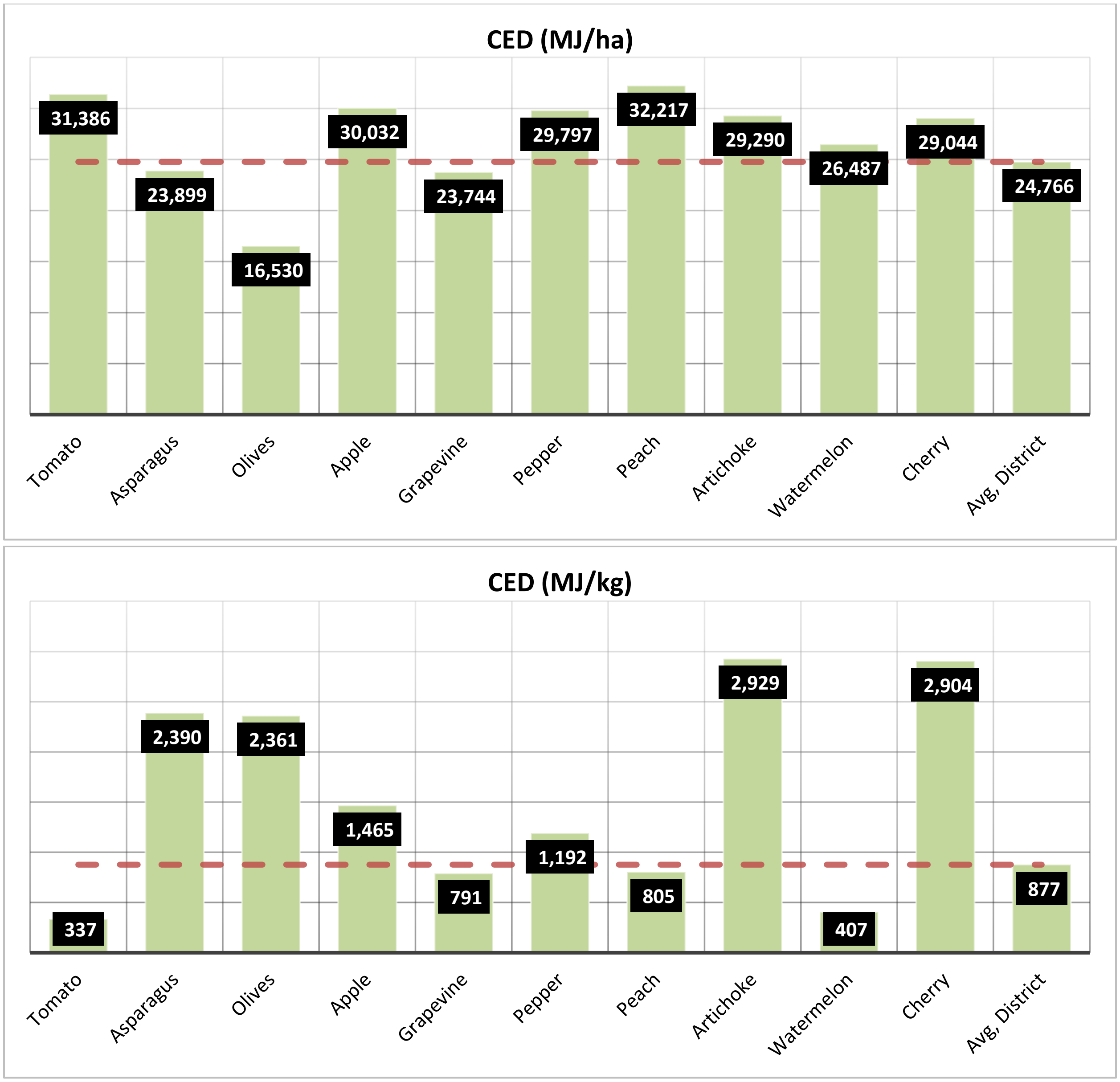


Fig. 15. Cumulative energy demand for different crops in district 1-a.

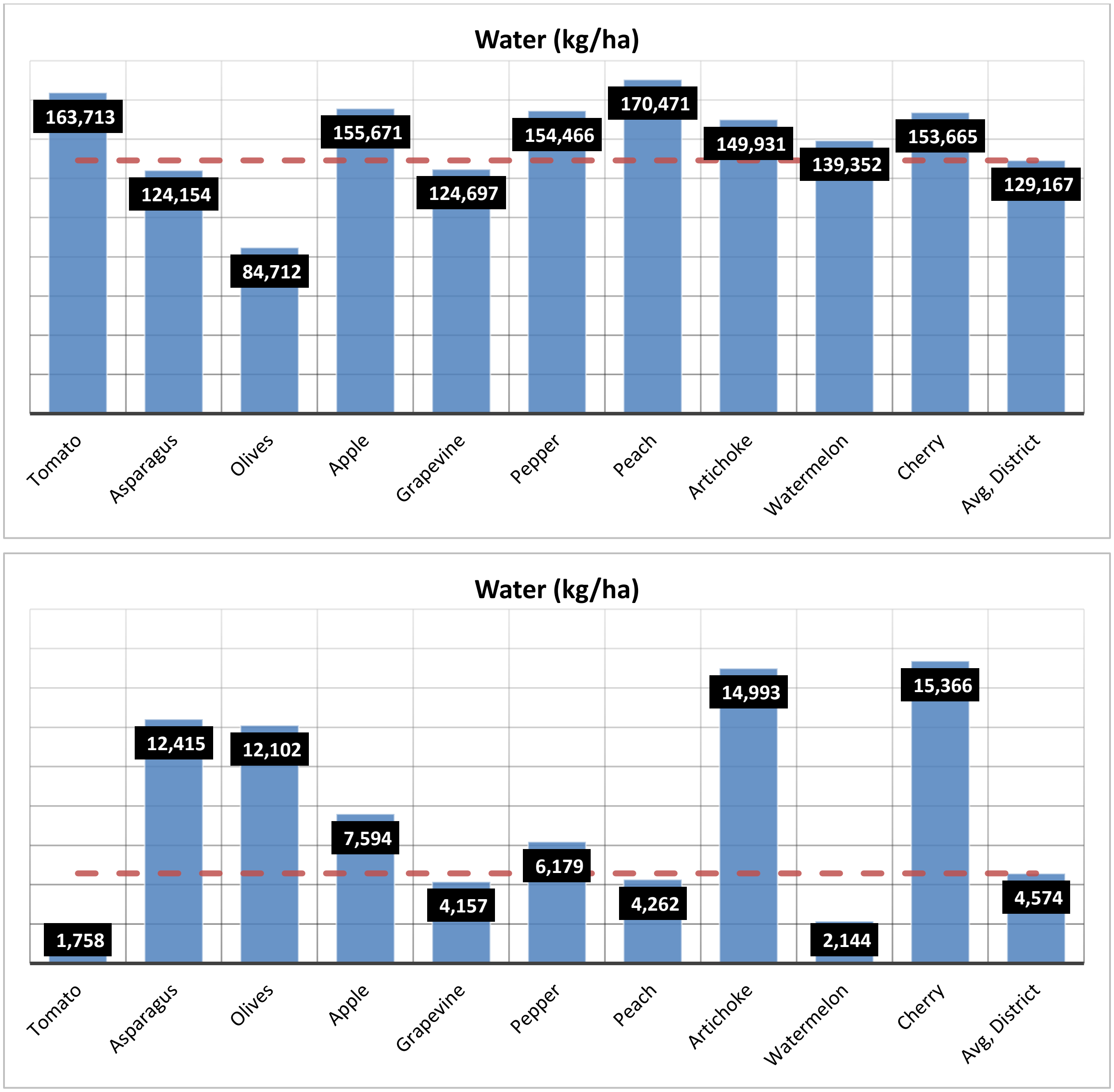


Fig. 16. Cumulative water demand for different crops in district 1-a.

Fig. 17 shows that the major CED for irrigation district comes from nitrogen fertilizer (37%) and electricity for irrigation (34%). For water, demand comes from fertilizer (34%) and electricity for irrigation (36%). Overall, 60% of CED comes from NPK fertilizers, 34% from irrigation water and electricity for pumping, and the rest from mechanization and pesticides. These results are very similar to water demand where 59% of demand comes from NPK fertilizers, 36% from irrigation water and electricity for pumping, and the rest from mechanization and pesticides. Since CBC is responsible for water supply and manages the pumping station, all the impacts of irrigation water and electricity for pumping are attributed to this actor.

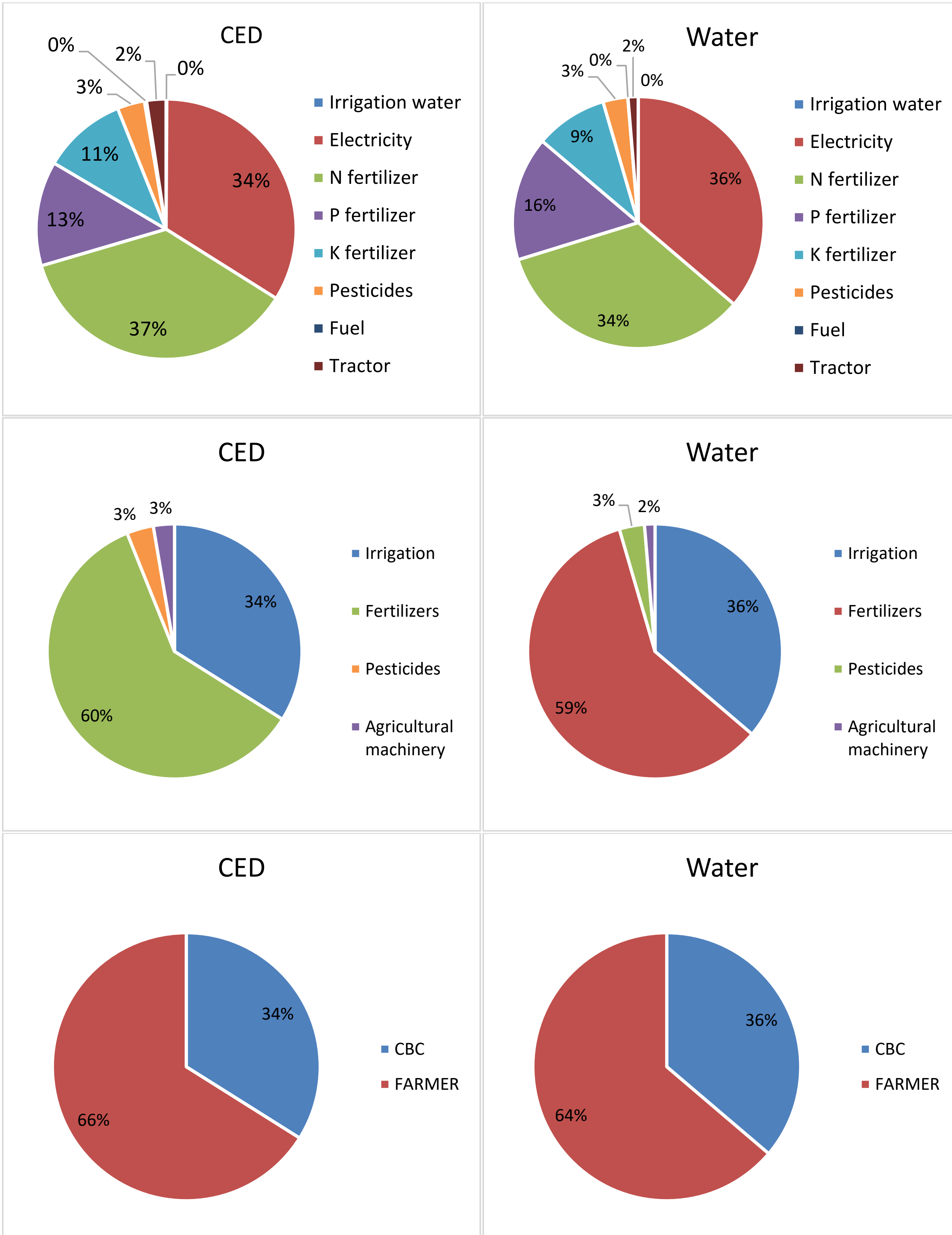


Fig. 17. Cumulative water and energy demand for irrigation district at process and actor level.

Fig. 18 shows the process contribution analysis for each crop. The effect of electricity on irrigation to CED range from 14% to 48%. For water, these effects range from 15% to 51%. As expected the effects of the crops with lower irrigation water requirements (e.g. olive, artichoke) the h linked to the production of nitrogen.

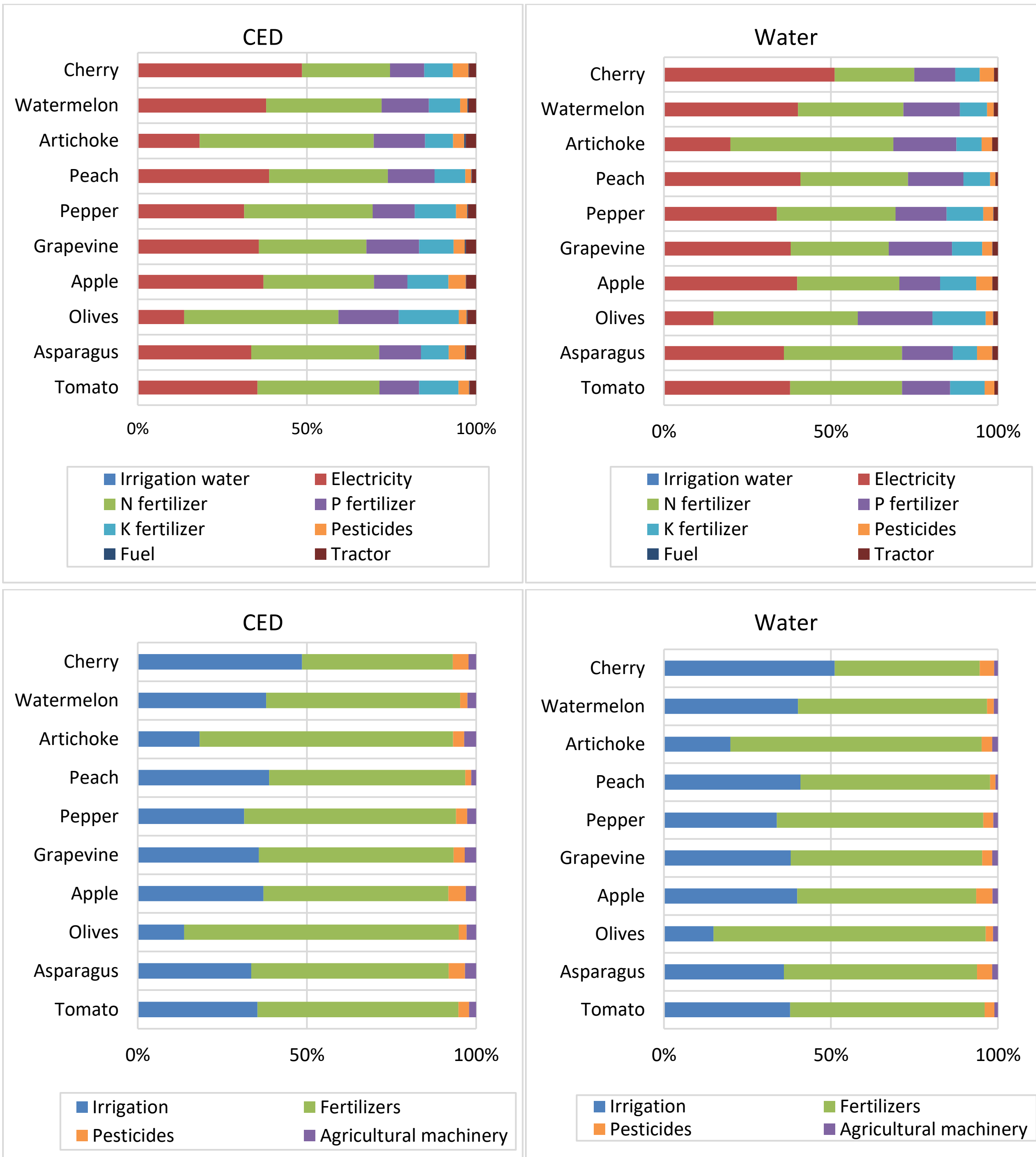


Fig. 18. Cumulative water and energy demand for crops at the process level.

4.3 LCA impacts

The comparative results of the LCA, as cradle-to-gate impacts, for the crops are shown in Table 11 (expressed as 1 kg of freshly harvested product). This analysis is used for benchmarking and put in evidence the differences among crop products. For 1 ha, the highest footprint is related to the production of Artichoke and tomatoes. For 1 ton, the highest footprint is related to the production of Artichoke and Olives.

Table 11. Life cycle impact scores of crop production in district 1-a per 1 kg of product at the farm gate.

Physical indicators	Tomato	Asparagus	Olives	Apple	Grapevine	Pepper	Peach	Artichoke	Watermelon	Cherry
ALOP	0.022	0.160	0.208	0.087	0.052	0.082	0.053	0.251	0.027	0.148
GWP	41.4	305.5	332.9	165.6	95.3	152.2	96.2	453.8	50.1	309.7
FDP	7.4	54.1	55.2	29.7	18.4	26.9	17.0	73.1	9.3	62.2
FETP	0.41	2.92	3.44	1.72	0.96	1.50	0.95	4.10	0.49	3.08
FEP	0.016	0.133	0.177	0.070	0.046	0.059	0.038	0.156	0.022	0.137
HTP	9.6	69.3	84.0	40.7	23.0	35.5	22.1	98.6	11.4	71.0
IRP	2.95	21.38	19.80	12.35	7.34	10.45	7.13	26.12	3.75	26.69
METP	0.38	2.71	3.22	1.59	0.89	1.39	0.88	3.83	0.45	2.83
MEP	1.13	8.38	9.85	4.46	2.42	4.18	2.67	13.57	1.32	7.35
MDP	2.57	19.02	23.12	10.89	6.23	9.68	5.79	28.02	3.09	18.59
NLTP	0.0011	0.0078	0.0099	0.0047	0.0026	0.0041	0.0026	0.0111	0.0013	0.0082
ODP	4.03E-06	3.33E-05	2.76E-05	1.90E-05	1.02E-05	1.48E-05	8.47E-06	3.97E-05	4.79E-06	3.89E-05
PMPF	0.125	0.935	1.093	0.484	0.291	0.469	0.288	1.482	0.152	0.872
POFP	0.119	0.925	1.020	0.417	0.323	0.459	0.260	1.462	0.160	0.933
TAP	0.668	4.961	5.850	2.633	1.456	2.489	1.547	8.001	0.783	4.414
TETP	0.022	0.160	0.208	0.087	0.052	0.082	0.053	0.251	0.027	0.148
ULOP	41.4	305.5	332.9	165.6	95.3	152.2	96.2	453.8	50.1	309.7
WDP	7.4	54.1	55.2	29.7	18.4	26.9	17.0	73.1	9.3	62.2

GWP: global warming potential; ODP: ozone depletion potential; PMFP: particulate matter formation potential; POFP: photochemical oxidant formation potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; TAP: terrestrial acidification potential; FETP: freshwater ecotoxicity potential; METP: marine ecotoxicity potential; TETP: terrestrial ecotoxicity potential; FDP: fossil depletion potential; MDP: mineral depletion potential; WDP: water depletion potential; ALOP: agricultural land occupation potential; NLTP: natural land transformation potential; ULOP: urban land occupation potential; HTP: human toxicity potential; IRP: ionizing radiation potential]

The life cycle environmental impacts of producing 1 kg of the crop are dominated by fertilizers for climate change, particulate matter formation, freshwater eutrophication terrestrial acidification (Fig. 19). Irrigation processes (energy + water) were the major contributor's fossil fuel depletion, ionizing radiation, ozone depletion, and land occupation. The results of the analysis for different crops and some impact categories are summarized in Fig. 20.

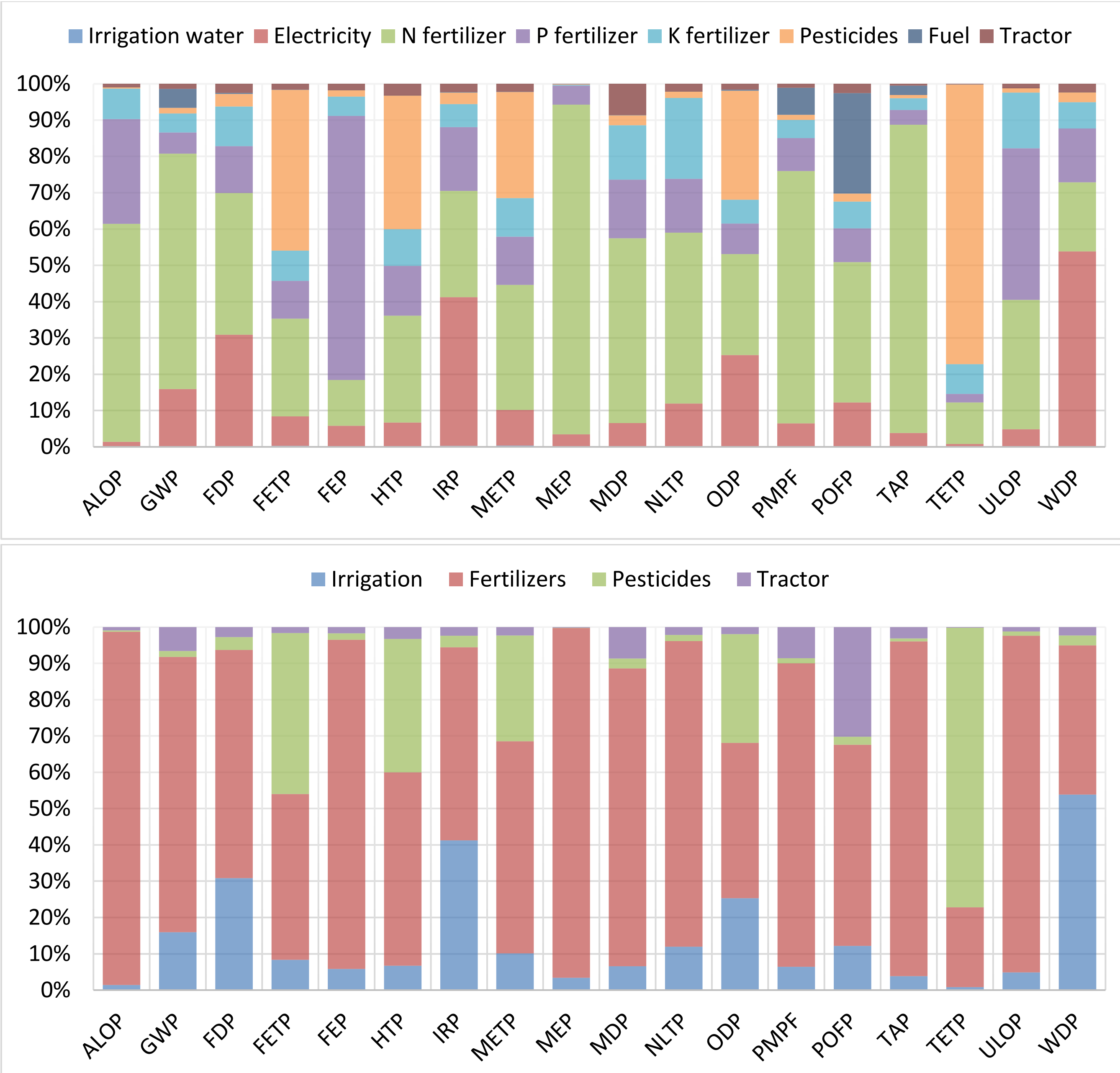


Fig. 19. Analysis of LCA-based impacts at the district level.

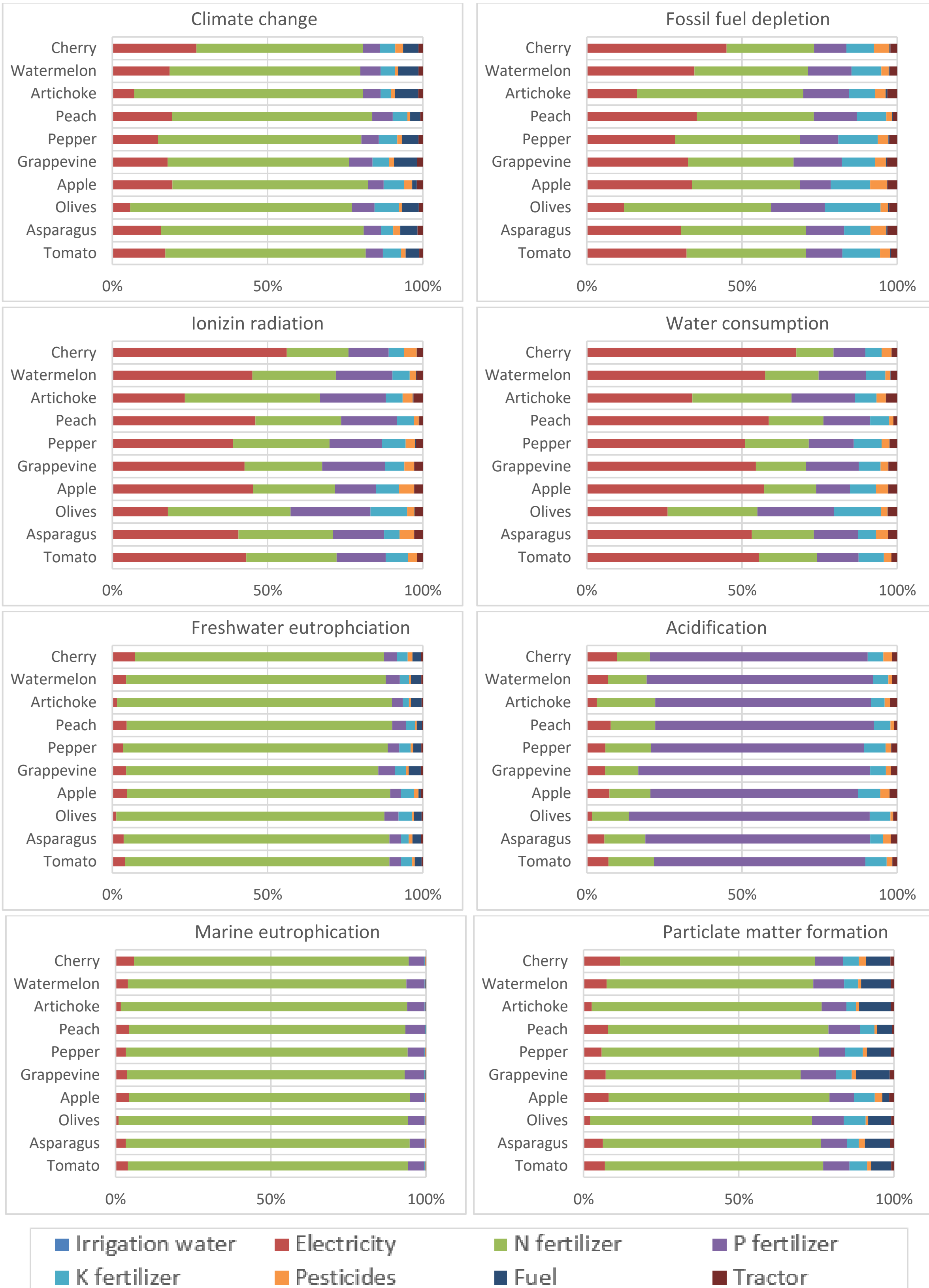


Fig. 20. Analysis of crop LCA-based impacts at the process level.

4.4 Environmental costs and weighted results

The LCA indicators were weighted and transformed into a single score using the Environmental Prices method. The monetized WEEN nexus indicators for each crop are presented in Fig. 21. The environmental cost varies from about 17.8 €/ton for the tomato to 206.7 €/ton for Artichoke. The average environmental cost for 1 kg generic cultivation was estimated at 88 €/ton. The environmental cost will be higher for low yield crops.

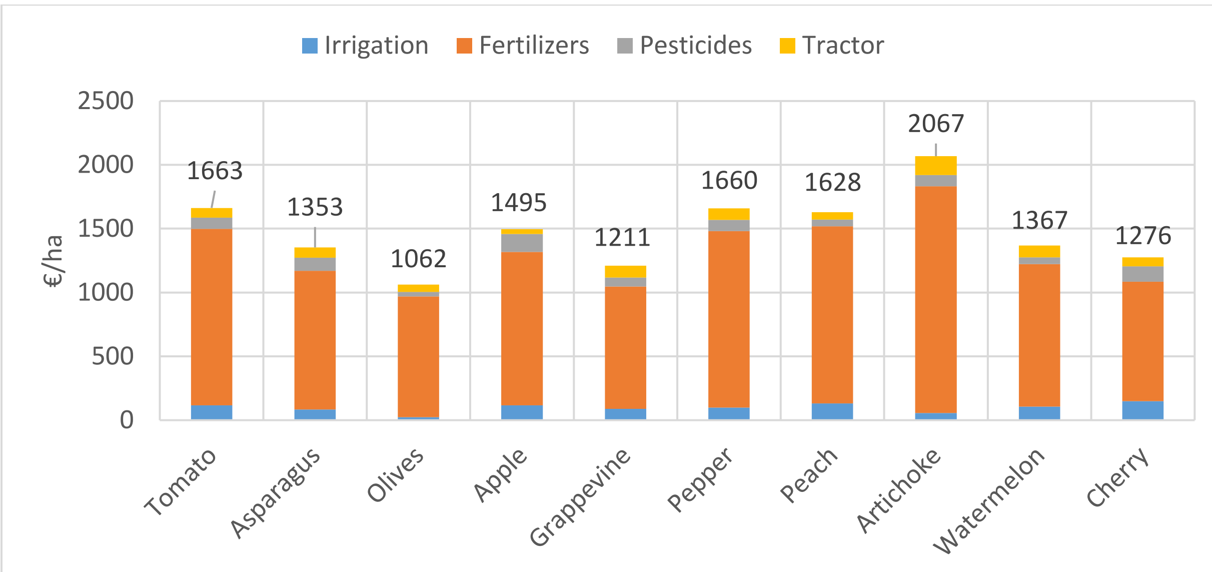


Fig. 21. Environmental life cycle costs per process at the crop level for 1 ha of cultivated land.

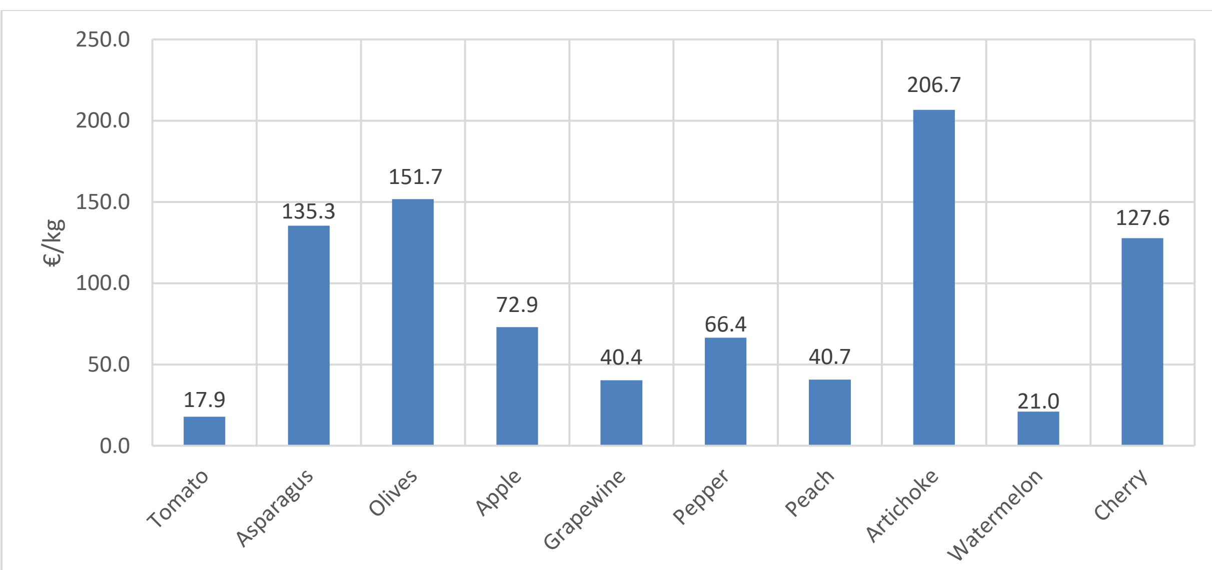


Fig. 22. Cumulative Environmental life cycle costs at the crop level per 1 kg at the farm gate.

The weighted results for the irrigation scheme (Fig. 23) showed that about 5.8% (77.7 €/ha) of the environmental cost is generated from electricity consumption for irrigation managed by CBC. The higher the water pumped, the higher will be the additional environmental impact from energy.

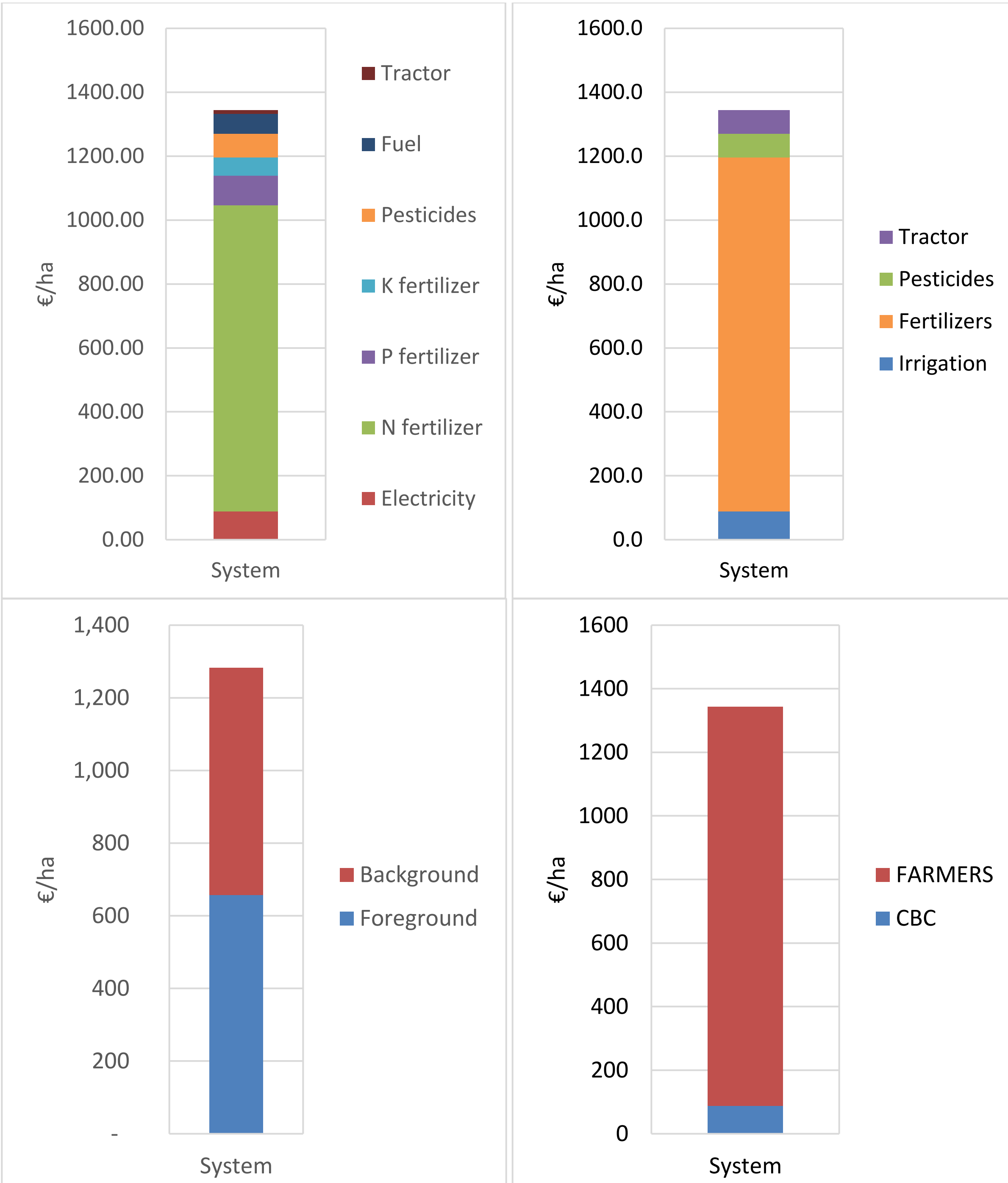


Fig. 23. Analysis of environmental life cycle costs at the process, actor, and sub-system level.

For each kWh reduced 0.11 € in terms of environmental costs could be saved. The effects of fertilizers considerably larger than electricity. For only production of 1 kg nitrogen, phosphates, and potassium the

benefits are 2.41, 2.93, and 1.06 €/kg, respectively. Further environmental costs could be saved from avoided fertilizer application and associated emission in the field. Production, transportation, and use of mineral fertilizers contribute significantly directly and indirectly to global warming, human toxicity, particulate matter formation categories as well as acidification translating these impact categories as the main contributor to environmental costs.

5 Concluding remarks from nexus analysis

With a 'nexus lens' and a multi-indicator Life cycle assessment (LCA) approach this study explored the water-energy-environment interaction of the Trinitapoli wastewater reuse scheme and assess the trade-offs and potential nexus synergies in front of a no reuse scenario. The analysis was useful for sound and effective communication of LCIA results, however, they should be taken as "indicative" or 'what-can happen' scenario due to the high uncertainty associated with them. Still, LCA results confirm the reality in most Mediterranean countries with current unsustainable patterns of current water use and agricultural practices. The LCA results, shown in many different levels of detail (midpoint, endpoint, and single-score results) confirmed that on the midpoint level local benefits associated with water and nutrient recycling (fewer impacts of water consumption and marine eutrophication) outweigh the global impacts from reclaimed water treatment. This is triggering net local benefits in terms of local water consumption and scarcity (non-natural resource, withdrawal water has no impact) and marine eutrophication (less secondary water released to the sea), which are not offset by higher upstream (global) environmental impacts such as cumulative energy demand, mineral resources, and toxicity-related impact categories.
The implementation of wastewater reuse leads to a shift in environmental impacts, reducing direct or "local" emissions/impacts at the agriculture site and increasing indirect or "global" emissions from the supply of electricity, chemicals, and infrastructure. Aggregating midpoints at the end of this cause-effect chain to the three endpoint impact of human health, ecosystem damage, and resource depletion and single-score results show that the benefits of wastewater reuse outweigh the impacts which mainly result from a cause-effect chain of water consumption impacts (supplying additional water without increasing local water scarcity) indicating that in this water-scarce area direct water savings are far more important for the overall sustainability reuse strategy. On the contrary, local water resources would be more stressed without reuse as groundwater has to be ruthlessly exploited for supplying agriculture with system-wide cascading effects on agricultural production and the local economy. Crediting the avoided burden (stopping groundwater withdrawals) magnifies the advantages of wastewater reuse allows minimization of the impacts and overall better environmental sustainability performance. Wastewater reuse involves significant benefits (avoided costs) from preventing the discharge of pollutants into the environment which typically produces environmental damage in terms of human health, environmental quality, and productive activities if inadequately managed. This means social non-market benefits would already justify the implementation reuse in economic terms that integrating monetary evaluation of environmental impacts gives additional insight on the full economic feasibility of some projects. Although the level of acceptance of wastewater reuse in Southern Italy is generally high and the multi-year demonstration activities have shown no negative effects, up to nowadays, effective implementation of

water reuse operations has been a big challenge because of the complexity of the systems and adoption of decisions seen as politically and economically driven issue.

The nexus analysis was extended to the crop's production system. The machinery, diesel fuel, fertilizer, pesticides, and irrigated water inputs per hectare in the crop's production system were considered in the calculation of cumulative energy demand, cumulative water demand, and several midpoint environmental impacts such as climate change, acidification, and human toxicity. Irrigation is also an important driver for some environmental impacts, however, the multi-impact analysis and weighted results demonstrated that the effect of irrigation remains very low since the surface water supply is implemented. If combined use of both surface water and groundwater is implemented larger effects of irrigation could be expected. Apart from irrigation, delivering nutrients is also energy-intensive with consequent direct emissions to the environment. Hence efficient strategies to control water and nutrient supplies will decrease energy inputs and avoid pollution triggering environmental and socio-economic benefits.

The level of environmental impacts on the irrigation scheme will depend on the annual agronomic practices adopted. Therefore, the contribution of this thesis is mainly methodological (qualitative) rather than numerical (quantitative). The modeling approach used in this study proved a very useful tool to analyze the nexus performance of crop production and the overall irrigation scheme. By looking at monetized LCA impacts, a new perspective was added to the nexus sustainability performance. We recommend further similar research to explore the impact of the conjunctive use of water resources and crop-fertilizer interactions

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