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Review

Environmental Assessment of Wastewater Treatment and Reuse for Irrigation: A Mini-Review of LCA Studies

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Abstract: This paper provides an overview of existing LCA literature analyzing the environmental impacts of wastewater treatment and reuses, with irrigation as a process or scenario. Fifty-nine ($n = 59$) papers published between 2010 and 2022 were reviewed to provide insights into the methodological choices (goals, geographical scope, functional units, system boundaries, life cycle impact assessment (LCIA) procedures). The results show that LCA research has steadily increased in the last six years. The LCAs are case-study specific, apply a process perspective, and are primarily conducted by European authors. The LCAs are mainly midpoint-oriented with global warming, acidification and eutrophication potential as the most common impact categories reported. Volumetric-based functional units are the most widely applied. The most commonly used LCIA models were ReCiPe and CML, with Ecoinvent as the most commonly used database and SimaPro as the primary LCA software tool. Despite the fact that these methods cover a wide range of midpoint impact categories, nearly half of the studies focused on a few life cycle impact category indicators. In many studies, the LCA scope is frequently narrowed, and the assessment does not look at the cradle-to-grave system boundary but rather at cradle-to-gate or gate-to-gate system boundaries. Regardless of technology or other system boundary assumptions, the design of environmentally efficient wastewater reuse schemes is primarily determined by the type of energy supplied to the product's life cycle. Our findings highlight that more holistic studies that take into account the expansion of system boundaries and the use of a broad set of environmental impact categories, supported by uncertainty and/or sensitivity analysis, are required. The overview presented in this paper serves as groundwork for future LCA studies in the field of irrigation with treated wastewater.

Keywords: review; life cycle assessment (LCA); wastewater treatment; water reclamation; irrigation; water reuse

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1. Introduction

Water is essential for agricultural production and plays an important role in food security. Food consumption is increasing in most parts of the world as a result of population growth and dietary changes, which has a direct impact on agricultural resource scarcity and distribution. As pointed out by the FAO [1], farming accounts for almost 70 percent of all water withdrawals, and up to 95 percent in some developing countries.

By 2050, irrigated food production will have to increase by more than 50 percent [1]. Climate change is expected to exacerbate water scarcity and competition for water resources. Wastewater is frequently regarded as a valuable resource of the emerging circular economy approach. It may be helpful in alleviating water scarcity in arid and semi-arid Mediterranean countries [2]. It is appealing for toilet flushing, agricultural and landscape irrigation, industrial processes, and replenishing/recharging of groundwater basins [3].

The reuse of treated wastewater for irrigation has a long history of development and has undergone different phases in developing and developed countries [4]. To address water scarcity, 15 million m^3/day of untreated wastewater is used globally for crop irrigation [5]. About 44 countries worldwide already use wastewater for crop irrigation [6]. It is extensively applied in China, Pakistan, Colombia, Syria, South Africa, Morocco, and Peru [7]. Irrigation with treated wastewater is also successfully practiced in Cyprus, Italy, Malta, Israel, the United States, Mexico, and Chile [7].

Untreated wastewater irrigation can cause a slew of environmental issues [4]. On the other hand, the standards set by local governments for wastewater are becoming more stringent. Advanced tertiary treatments must be implemented in conventional wastewater treatment plants to optimize water quality for reuse in agricultural irrigation. Improved water quality and water-related services are frequently associated with increased electricity and chemical demand, together with associated environmental emissions. Yet, a large proportion of the environmental impact occurs for processes in the upstream supply chain (e.g., material production for infrastructure). As a result, the resource utilization and environmental effects in a life cycle outlook is highly necessary an integrated view. Moreover, in crop production, the comparison of environmental life cycle impacts from linear product versions with their circular counterparts is required to ascertain the environmental consequences and to provide scientific guidance for the sustainable utilization of reclaimed water [8].

Life cycle assessment (LCA) is a tool that can be used to evaluate an environmental load of a product, process, or activity throughout its life cycle. LCA is instrumental to evaluate the environmental sustainability of water-related technologies services and by capturing tradeoffs across various categories of environmental concern [9]. Studies that assess the environmental impacts of wastewater treatment and reuse for irrigation through LCA are becoming more common in the literature. Nevertheless, a summary and review of such LCA studies have been partially reported in scientific literature. LCA studies related to municipal wastewater management and wastewater treatment were previously reviewed by other authors [9–12]. In this work, we explored how LCA has been applied in the context of wastewater treatment and reuse when irrigation is included as a process or as a scenario. The findings contribute to the identification of trends and opportunities in the field, as well as exchange of data and lessons for the next generation of LCA studies in the field of irrigation with treated wastewater.

2. Review of International Literature

This study used bibliographic databases such as "ScienceDirect" and "Web of Science" and "Google Scholar" for publications relating to the environmental impacts of wastewater treatment and reuse for irrigation published in the last 12 years (2010–2022). The review was performed using the search strings of "wastewater", "irrigation", "agricultural reuse", "LCA", "life cycle assessment" and "environmental impact" in title, abstract, and keywords. After searching the databases, a total of fifty-nine (59) studies were selected and reviewed. Only studies including an impact assessment phase were selected.

2.1. Type of Research

Most LCA articles were published in peer-reviewed journals such as the *Journal of Cleaner Production* [12–22], *Science for Total Environment* [23–29], *Journal of Environmental Management* [30–32], and other environmental/ecological [33–42] and water-related journals [38,43–50]. Conference papers and report account for only a very small percentage of LCA studies [51–55].

2.2. Study Objective and Processes

The majority of LCA studies take a process-oriented approach, focusing on the design and operation of a wastewater treatment plant and its recovery processes. Most published research is case-study-specific. The study objective, as can be seen in Table 1, is divided into wastewater treatment designated for reuse [14,33,34,38,44,56–58], reuse of effluent for crop irrigation [8,21,24,26,46,53,59–62] or to elaborate LCA-related tools and framework for the evaluation of wastewater reuse environmental efficiency [12,24,49]. Filtration with or without UV disinfection [12–14,25,26,29,31,33,54,57,62,63], ozonation [25,27,33,38,58], coagulation–flocculation [22,43,51,56,58], and constructed wetlands [23,30,35,41] are some of the common processes studied.

Table 1. List of LCA studies on wastewater treatment and reuse including irrigation.

Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Arias et al. [43]	2020	Benchmark the environmental and economic profiles of a resident living in a neighborhood with centralized or decentralized wastewater treatment systems according to four different schemes.	Spain	ISO 14044, 2006/AMD 1:2017	ReCiPe 2016 mid-point (H)	SimaPro v9	Ecoinvent v3.5	Only operation	1 resident living in the neighborhood served by centralized/decentralized treatment	Yes
Thompson et al. [44]	2022	Evaluate and compare the environmental LCA impact of different mechanical WRRFs and lagoons.	USA	ISO 14040/ISO 14044	TRACI v2.1	OpenLCA v1.7	Ecoinvent v3.6	Infrastructure + operation	1 m^3 of treated wastewater	Yes
de Morais LimA et al. [23]	2022	Environmental performance of the current wastewater treatment in Campo Grande city irrigation of eucalyptus plantations with the treated effluent.	Brazil	ISO 14040/ISO 14044	ReCiPe 2016	SimaPro v9.1	Ecoinvent	Only operation	Domestic effluent generated by one household (four inhabitants) for one year	Yes
Roman and Brennan [30]	2021	Explore the environmental impacts of operating a pilot-scale treating municipal wastewater for producing animal feed (derived from duckweed) and irrigation water (derived by UV disinfection of the treated effluent).	USA	-	Impact 2002+	SimaPro v9.0	Ecoinvent v3.6	Infrastructure + operation	Million liters (ML) of wastewater treated	Yes
Maeseele and Roux [12]	2021	To elaborate a robust and homogeneous framework for the evaluation of WW-reuse environmental efficiency and application in a few worldwide archetype situations.	Different climates	ISO 14040/ISO 14044	ReCiPe 2016	SimaPro v9	Ecoinvent v3.5	Only operation	1 m^3 of water at the user gate (irrigated plot)	Yes
Kalboussi et al. [24]	2022	Introduce LCA as an analytical tool to identify the conditions under which reclaimed water reuse for irrigation is environmentally efficient by comparing reclaimed water with river and groundwater.	France	ISO 14040.	ILCD 2011	SimaPro v9.1.1	Ecoinvent v3.6	Infrastructure + operation + end-of-life	1 ha of vineyards	Yes
Romeiko [8]	2019	Compare life cycle environmental impacts of crop systems irrigated with groundwater and reclaimed water.	China	ISO guidelines	IPCC, USEtox, ReCiPe 2016	GREET.net and SimaPro	Ecoinvent v3	Only operation	1 kg of grain	Yes

Table 1. *Cont.*

Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Carré et al. [33]	2017	Compare the environmental impacts of different options of tertiary treatment processes for water reuse in unrestricted irrigation.	France	ISO 14040/ISO 14044	ReCiPe 2008	GaBi v5	Ecoinvent v2.2	Infrastructure + operation + end-of-life	To supply 1 m^3 of water with quality in compliance with the highest standard of the French reuse regulations	No
Arzate et al. [25]	2019	Comparative analysis between the ozonation and the photo-Fenton process as tertiary wastewater treatment processes used to reclaim wastewater for agricultural irrigation.	Spain	ISO 2006	ReCiPe 2016 Midpoint & Endpoint (H) V1.13; USEtox (recommended + interim) V1.04	SimaPro v9	Ecoinvent v3.3	Infrastructure + operation + end-of-life	Disposal of 1 m^3 of secondary effluent	No
Moretti [26]	2019	Evaluate and compare life cycle environmental impacts of fruit orchards irrigated with surface water and reclaimed water.	Italy	ISO standards 14044:2006	AWARE, IPCC 2007, USEtox, Accumulated Exceedance	SimaPro v8.4	Ecoinvent v3	Only operation	1 kg of nectarines	Yes
Arcidiacono and Porto [60]	2011	Evaluation of the incidence of the different stages of the process on the overall environmental burden of biomass production when using treated wastewater.	Italy	ISO 14040:2006	Eco-indicator 99	SimaPro v8.4	Ecoinvent	Not included	1 ton of biomass	Yes
Azeb et al. [45]	2020	Compare the environmental performance of cucumber production when using reclaimed water mixed with surface water and groundwater, and to analyze fertilization practices used by farmers in the region.	Algeria	ISO 14040 standards	ReCiPe 2016	SimaPro 7.1	Ecoinvent v3	Not included	1 ha and 1 kg of cucumber	No
Canaj et al. [13]	2021	Physical and economic life cycle assessment (LCA) of agricultural wastewater reuse for irrigation and comparing with a no-reuse scenario.	Italy	ISO 14040/ISO 14044	ReCiPe 2016	openLCA v1.10.2	Ecoinvent v3.1	Infrastructure + operation + end-of-life	1 m^3 of water of suitable quality for irrigation in agriculture	Yes
Canaj et al. [46]	2021	Environmental and economic analysis of table-grape cultivation when using a linear production system (100% groundwater) and as a circular process (50% treated wastewater and 50% groundwater).	Italy	ISO 14045:2012	Environmental Footprint (EF) method 3.0 (adapted)	openLCA v1.10.2	Ecoinvent v3.1	Infrastructure + operation + end-of-life	1 ton of table grapes delivered at the farm gate and 1 ha of cropped land	Yes
Canaj et al. [59]	2021	Calculate the external environmental costs (EEC) and internal costs (IC) of crop cultivation irrigated with treated municipal wastewater.	Italy	-	ReCiPe 2016	openLCA v1.10.3	Ecoinvent v3.1	Infrastructure + operation + end-of-life	1 ton of product	No

Table 1. *Cont.*

Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Akhoundi and Nazif [15]	2018	Sustainability assessment of wastewater reuse.	Iran	-	Eco-Indicator 99	SimaPro v8	-	Infrastructure + operation	1 m^3/day of WWTP's secondary effluent	Yes
Akhoundi and Nazif [34]	2020	LCA of tertiary treatment technologies to treat secondary municipal wastewater for reuse in agricultural irrigation.	Iran	ISO 14040	Impact 2002+	SimaPro v8	Ecoinvent	Infrastructure + operation	Production of an average of 1 m^3 = day of WWTP effluent during 20 year	No
Büyükkamaci and Karaca [47]	2017	Assess the environmental impacts of some effluent polishing units for the reuse of treated wastewater for agricultural irrigation of sensitive crops.	Turkey	ISO 14000	CML 2001	GaBi v6.1	Ecoinvent	Only operation	1 m^3 of recycled water to be used for irrigation	No
Opher and Friedler [31]	2016	Compare the consequences of the implementation of four different hypothetical high-level urban wastewater management policies using LCA.	Israel	-	ReCiPe Mid-point, v.1.07	SimaPro v8	Ecoinvent	Infrastructure + operation	Supply, reclamation, and reuse of water consumed by the modeled city during one year	Yes
Opher et al. [64]	2018	Comparative life cycle sustainability assessment of urban water reuse at various centralization scales.	Israel	-	ReCiPe Mid-point, v.1.07	GaBi v6	Ecoinvent	Only operation	Annual supply, reclamation, and reuse of water consumed by a model city	Yes
Foglia et al. [14]	2021	Sustainability of the different water reclamation and reuse practices in terms of environmental and economic impacts.	Italy	ISO14044	ReCiPe 2008 Mid-point (H) v1.13 no LT	Umberto LCA v10.0	Ecoinvent v3.6	Only operation	1 m^3 of treated wastewater	No
Kamble et al. [35]	2017	Analyze the environmental impacts associated with the treatment of wastewater in a soil-biotechnology plant.	India	(ISO 14040 2006a; ISO14044 2006b)	CML 2001	GaBi v6	GaBi database	Infrastructure + operation	1 m^3 of wastewater to be treated	No
Laitinen et al. [41]	2017	Compare climate change impacts and economic feasibility of a constructed wetland (CW)-based wastewater treatment plant to an activated sludge process (ASP) for crop irrigation.	Mexico	ISO 14040; ISO 14044	IPCC 2007	GaBi v6	Ecoinvent	Only operation	1000 m^3 of influent wastewater	Yes
Tabesh et al. [65]	2019	Identify the critical sources of environmental impacts and compare energy sources in Tehran's WWTP, and compare the possible environmental burdens caused by discharging the treated wastewater into the river with impacts created by using treated wastewater for irrigating the farmlands.	Iran	ISO14044	Eco-Indicator 99	SimaPro v7.1.8	-	Only operation	Day of operation.	No

Table 1. *Cont.*

Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Amores et al. [16]	2013	Assess the environmental profile of an urban water cycle in a Mediterranean city including reuse phase with tertiary treatment and irrigation in agriculture.	Spain	ISO14040 and ISO14044	CML 2001, CED	-	Ecoinvent v2.1	Only operation	1 m^3 of potable water supplied to the consumers	No
Buonocore et al. [42]	2018	LCA is applied to compare the environmental performance of different scenarios for wastewater and sludge disposal in a WWT plant located in Southern Italy.	Italy	ISO 14040-44 standards	ReCiPe 2008	OpenLCA	Ecoinvent v2.2	Infrastructure + operation + end-of-life	1000 m^3 of wastewater	No
Muñoz et al. [66]	2010	Compare LCA impacts of tobacco biomass production using different water sources: groundwater, treated wastewater, and desalinated seawater.	Spain	ISO 14044	CML 2000, USES–LCA	-	Ecoinvent v2	Only operation	1 kg of aboveground tobacco biomass in a 1935 m^2 Mediterranean greenhouse	Yes
Kraus et al. [53]	2013	LCA, water footprint, and quantitative microbial and chemical risk assessment of water reuse schemes in Europe.	Germany/ UK/ Belgium/ Spain/ Israel	ISO 14040/ISO 14044	ReCiPe 2016, USEtox, AWARE, CED	-	Ecoinvent v3.1	Infrastructure + operation	m^3 additional water supplied; 1 m^3 of water with an optimal quality to be reused	Yes
Miller-Robbie et al. [36]	2017	Energy use and GHG emissions per liter for the combination of wastewater treatment and reuse in agriculture and compare irrigation waters of varying qualities (treated wastewater, versus untreated water and groundwater).	India	-	TEAM and DAY-CENT	-	-	Only operation	1 year of operation	No
Meneses et al. [56]	2010	Evaluate different disinfection treatments (chlorination plus ultraviolet treatment, ozonation, and ozonation plus hydrogen peroxide) and assess the environmental advantages and drawbacks of urban wastewater reuse in non-potable applications.	Spain	ISO14044	CML 2000	-	Ecoinvent v2.1	Only operation	1 m^3 of reclaimed water produced at the plant for nonpotable applications	Yes
Polruang et al. [17]	2018	A comparative LCA of municipal WWTP in Thailand under variable power schemes and effluent management programs.	Thailand	ISO 2006	CML-IA	-	Ecoinvent v3	Only operation	1 m^3 of the effluent	Yes

Table 1. *Cont.*

Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Lane et al. [48]	2015	The environmental profiles of two city-scale urban water systems: one relying on freshwater extraction and most treated wastewater being discharged to the sea, and the other that adopts a more diverse range of water supply and wastewater recycling technologies including agricultural reuse.	Australia	ISO14044	ReCiPe 2008	-	AUSLCI/ Ecoinvent	Infrastructure + operation	Provision of water supply and wastewater management services, for a one-year period, to an urban population in the Gold Coast region of Australia	No
Raghuvanshi et al. [52]	2017	LCA of the treatment process to reuse of water for irrigation at a university campus.	India	(ISO) 14040	ReCiPe	Umberto NXT Univer-sal	Ecoinvent v3	Only operation	1500 m^3 of WW per day	No
Lam et al. [18]	2015	Compare source-separation systems with other domestic wastewater management systems from a life cycle perspective.	China	-	LIME-2	-	ELCD, Japan, China	Infrastructure + operation	Wastewater (urine, feces, and gray water) discharged annually by one person	No
Cornejo et al. [32]	2013	Evaluate the potential benefits of mitigating the environmental impact of two small community-managed wastewater treatment systems in rural Bolivia using resource recovery (i.e., water reuse and energy recovery).	Bolivia	ISO 14040	IPCC, CED, and Eco-indicator 95	SimaPro v7.2	Ecoinvent v2.2	Infrastructure + operation	1 m^3 of treated wastewater over a 20-year lifespan	Yes
Jeong et al. [19]	2018	LCA of small-scale graywater reclamation systems and evaluation of the life cycle environmental impacts of replacing potable water demand with reclaimed water for non-potable uses.	USA	-	TRACI v2.1	SimaPro v8	Ecoinvent v3/USLCI	Infrastructure + operation	1 m^3 water used for outdoor irrigation and/or toilet flushing	Yes
Muñoz et al. [27]	2009	Assess the environmental advantages and drawbacks of urban wastewater reuse in agriculture focusing on toxicity-related impact categories.	Spain	ISO 14044 standard	USES-LCA + EDIP	-	Ecoinvent v2.0	Only operation	1 m^3 for irrigation in agriculture.	No
O'Connor et al. [67]	2013	Environmental consequences of adding wastewater treatment stage at the mill and diverting this treated water to urban irrigation.	Australia	ISO 14040	ReCiPe 2008	SimaPro v7.3.2	Ecoinvent	Infrastructure + operation	1 m^3 of mill effluent; 1 m^3 of irrigation water to the urban irrigator	No
Shiu et al. [20]	2017	LCA for water reclamation and sludge recycling scenarios including agricultural irrigation.	Taiwan	ISO14040	CML 2 baseline 2000 (V2.05)	SimaPro v8.0.5	Ecoinvent v3.1	Only operation	1 m^3 of treated water	No

Table 1. *Cont.*

Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Singh et al. [37]	2019	Performance evaluation of a decentralized wastewater treatment system in India.	India.	ISO 14040-44	CML 2001	GaBi 6.0	GaBi database-	Only operation	1 m^3 of treated wastewater	No
Dong et al. [38]	2017	Compare the environmental impacts on human health stemming from two alternative disinfection technologies for landscape irrigational reuse.	USA	-	ReCiPe	SimaPro v8.0.5.13	Ecoinvent v3	Infrastructure + operation	Disinfection (more than 1 log10 inactivation) of 4 million gallons per day MGD of secondary effluent with a project lifetime of ten years	Yes
Kobayashi [39]	2020	Evaluate the environmental performance of various decentralized graywater management systems that could serve a greenfield community of 3500 person-equivalent (PE) in a cold region.	Canada	ISO14044	TRACI v2.1	OpenLCA v1.7	Ecoinvent v3.4	Infrastructure + operation	Annual treatment of graywater generated per person	Yes
Estevez et al. [68]	2022	Comparative environmental profile of centralized, decentralized, and/or hybrid configurations.	Spain	ISO 14040/44:2006	ReCiPe 2016 Mid-point and End-point methods V1.03 World (2010)	SimaPro v9	Ecoinvent v3	Only operation	Flow of wastewater to be treated in units $m^3 \cdot d^{-1}$	Yes
Bonilla-Gámez et al. [28]	2021	Quantify the environmental impacts of three different scenarios of resource supply in agro-urban frontier territories of semiarid regions under urban growth.	Argentina	ISO 14045	ReCiPe 2016	SimaPro v9.1.0.8	Ecoinvent v3.6	Only operation	Meet the average resource needs necessary to annually supply a use phase of 1 ha of an agro-services frontier territory in a semiarid region	Yes
Çetinkaya and Bilgili [40]	2022	Treatment of slaughterhouse industry wastewater with ultrafiltration membrane and evaluation with LCA.	Turkey	-	Impact 2002+	SimaPro v8.2.3	Ecoinvent v3	Infrastructure + operation	1 m^2 of soil	No
Giungato and Guinee [51]	2010	Assess the environmental advantages and drawbacks of urban wastewater reclamation in agriculture.	Italy	-	CML	GaBi v4.3	Ecoinvent v2	Only operation	Provision of 1000 m^3 of water for irrigation which complies with Italian limits	No
Santana et al. [22]	2019	Determine the environmental impacts of four distinct water management scenarios in a tourism-dependent community.	Spain	-	ReCiPe 2016 and AWARE	-	-	Infrastructure + operation	One year of operation for the entire water management system of Lloret de Mar	No

Table 1. *Cont.*

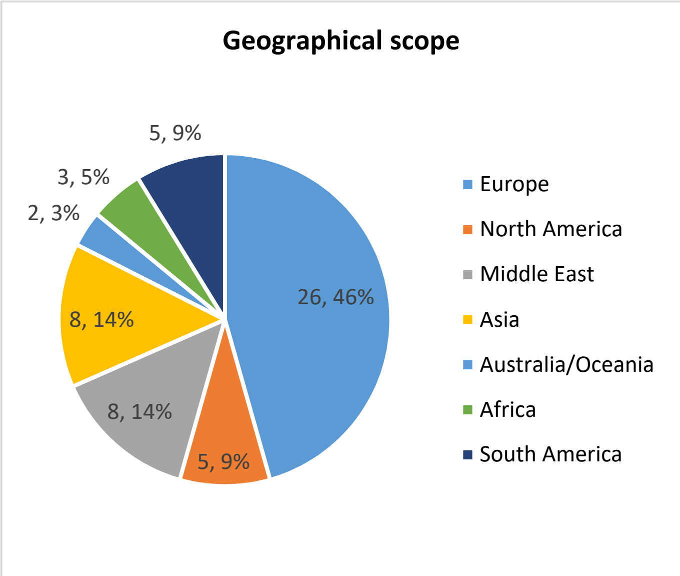
Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Rodríguez et al. [29]	2021	Evaluate the environmental performance of a simple filtration system to treat light graywater from rural areas affected by water scarcity	Chile	-	TRACI v2.1	OpenLCA v1.1	Ecoinvent 3.7/US EPA	Infrastructure + operation	1 m^3 of treated graywater	Yes
Uche et al. [21]	2015	Environmental impacts of water supply alternatives	Spain	-	Eco-Indicator 99	SimaPro v7.2.2	-	Infrastructure + operation	1 m^3 of water at the user's door (domestic, industrial, or irrigation)	No
Morsy et al. [69]	2020	Assess the environmental impacts of upgrading the wastewater treatment plants from primary to secondary treatment.	Egypt	ISO 14040 and 14044	ReCiPe 2008	GaBi	GaBi database	Infrastructure + operation	1 m^3 of treated wastewater	No
Fang et al. [49]	2016	To quantify the environmental impacts of wastewater resource recovery and reuse in agricultural crops production and in aquifer recharge associated with the operation of Lynetten WWTP, located southeast of Copenhagen, Denmark.	Denmark	ISO 14040 and 14044	ILCD 2011 + USETox	-	Ecoinvent	Infrastructure + operation	1 m^3 of influent wastewater	Yes
Rezaei et al. [63]	2019	Evaluate the tradeoff between reclaimed water quality and corresponding costs, environmental impacts, and social benefits for different types of water reuse applications.	USA	-	-	-	-	Only operation	-	Yes
Pergola et al. [62]	2013	Compare LCA of olive orchard growing under rainfed and microirrigated with urban treated wastewater.	Italy	ISO 14040	-	SimaPro v7.2	Ecoinvent	Infrastructure + operation	1 ha of farm land and 1 kg of olives	No
Frascari et al. [57]	2019	To perform an LCA and CBA of the proposed technology for phenolic compounds recovery, a scale-up of the adsorption/desorption process.	Italy	ISO 14040	ILCD 2011 Midpoint+ V1.10, IPCC 2013 GWP 20a V1.03, Ecological Scarcity 2013 V1.05, CED V1.09, Impact 2002+	SimaPro v8	Ecoinvent v3.3	Infrastructure + operation + end-of-life	1 m^3 of olive mill wastewater	Yes
Remy et al. [55]	2012	Analysis of the environmental footprint of the Braunschweig wastewater reuse scheme with LCA.	Germany	ISO 14040:14044	ReCiPe 2008/CED	Umberto v5.5	Ecoinvent v2	Only operation	Treatment of municipal wastewater per population equivalent and year, related to the influent load of chemical oxygen demand (COD) (120 g COD/(PE*a))	Yes

Table 1. *Cont.*

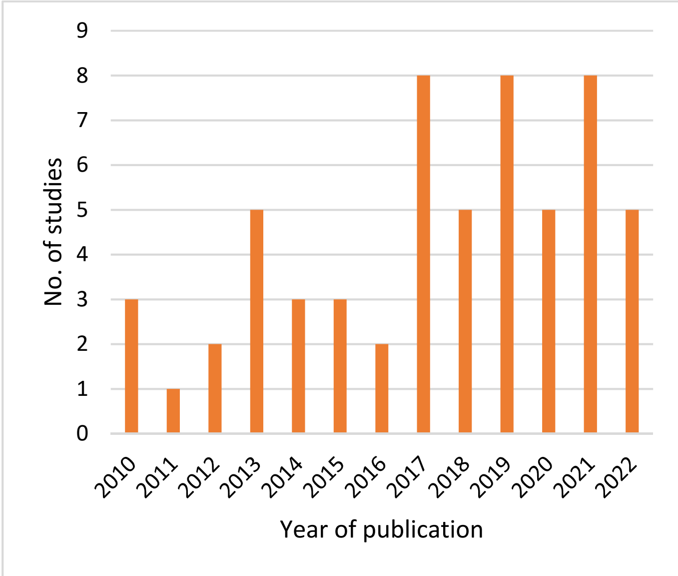
Author	Year	Goal of the Study	Location	LCA Standard Followed	LCIA Method	Software	LCA Database	Inclusion of Treatment System in System Boundaries	Functional Unit	Sensitivity
Vergine et al. [54]	2014	LCA of agricultural reuse of treated agro-industrial wastewater.	Italy	ISO 14040	-	-	-	Infrastructure + operation	1000 m^3 of water	No
Messaoud-Boureghda et al. [58]	2012	Assess the environmental performance of different processing technologies and to assess the effectiveness of the LCA as a tool to help decision-making in the framework of water recycling.	Algeria	ISO 14040:14044	Eco-indicators 95V2/Europe	SimaPro v6	-	Infrastructure + operation	5 L of recycled water intended to be used for irrigation	No
Uche et al. [50]	2014	LCA of the water supply alternatives and the water use in a water-stressed watershed in Spain.	Spain	-	ReCiPe 2008	SimaPro, v7.3.3	Ecoinvent	Infrastructure + operation	1 m^3 of water at the user's gate	No
Thibodeau et al. [61]	2014	Compare different development scenarios of a black water source-separation sanitation system (BWS) that could be environmentally and economically more viable than a conventional system (CONV).	Canada	ISO 14040:14044	IMPACT 2002 + v2.15	SimaPro, v7.3.3	Ecoinvent 2.2	Infrastructure + operation	To ensure wastewater and organic kitchen refuse collection and treatment and byproduct (digestate/sludge and biogas) recycling for one inhabitant for one year	Yes

2.3. Geographical and Temporal Scope

Geographical coverage of the reviewed studies varied (Figure 1), with the majority of the studies mainly carried out in the EU context (n = 26 or 46%). The European LCA analyses were mainly applied in Italy [13,14,26,42,46,51,54,57,59,60,62] and Spain [16,21,22,25,27,43,50,56,66,68] with eleven and ten studies, respectively. Two studies were conducted in France [24,33] and one in Germany [55]. Kraus et al. [53] presented the LCA results of different wastewater reuse schemes in Germany, United Kingdom, Belgium, Spain and Israel. About eight studies [15,31,34,40,47,53,65] were from Middle East, eight [8,17,18,20,35–37,52] from Asia, seven [19,30,38,39,44,61,63] in North America, five [23,28,29,32,41] in South America, two in Australia/Oceania [48,67], and three in Africa [45,58,69]. The literature has gradually been enriched over the years. The number of publications increased after 2016. This surge likely reflects the growing importance of wastewater due to water scarcity and drought events. Moreover, LCA has become one of the main pillars driving European policy concerning sustainable use of resources, sustainable consumption and production, and prevention of waste.



(a)



(b)

Figure 1. Geographical scope (**a**) and year of publication (**b**) of LCA studies on wastewater treatment and reuse including irrigation as a process or scenario.

2.4. System Boundaries, Multifunctionality, and Functional Units

A meaningful definition of system boundaries and functional units and equivalent scenarios for comparative studies are a prerequisite for an LCA, which should compare different technological options or processes in their environmental impacts [70]. System boundaries set the criteria and specify which unit processes are part of the product system. The most comprehensive definition of system boundaries reaches from the cradle (e.g., extraction of raw materials) to the grave (e.g., end-of-life treatment). For water treatment processes, a typical LCA framework includes the water flow to be treated (as input or "reference flow"), the treatment process itself, and all direct emissions into the environment (effluent water quality that is discharged or used in the environment, direct emissions to atmosphere), and all indirect processes that are required to build and operate this treatment process [70]. Since they vary widely, one of the challenges of LCA is delineating the system boundary. Most studies used a process perspective and have been established from a cradle-to-gate perspective and included only the construction of the infrastructure and the operation phase of the tertiary treatment, thus excluding the end-of-life for the constructed systems. Around 40% of the studies focused only on the operation phase of wastewater treatment system (See Table 1). The reason for excluding infrastructure was stated as a minor contribution to total impacts is negligible when compared to the operation phase or low contribution to impacts in previous studies [12,16,48,55,56], or because the wastewater treatment plant is operated no matter if its discharge is used or not for irrigation [8]. The end-of-life or disposal of spent consumables (e.g., membranes) and infrastructure were included to a limited extent [24,25,33,39,57]. Limited system boundaries that may not capture the full impacts of the processes and leave out certain life cycle stages in an LCA could lead to an incomparability of results [71].

Many LCAs [8,13,14,17,18,25,31,33,39,44–46,61,62,64,68] are of a comparative nature. More than 90% of studies cited that they based their analysis on international standards for LCA (ISO 14040/44:2006). The majority of LCAs did not explicitly state whether they used an attributional or consequential modeling approach.

Allocation is one common strategy for solving multi-functionality problems. In LCA there are two principal approaches to addressing secondary functions of a system, such as the production of reclaimed water as a secondary product of wastewater treatment: the "system expansion" approach and the "avoided burden" approach [53]. A first option to reach this functional equivalency is to expand the systems with alternative processes supplying the same function ("system expansion"). An example would be to expand the model of a reference wastewater treatment plant (WWTP) without water reuse with another process for water production (e.g., a drinking-water plant) so that this expanded system fulfills both functions of wastewater treatment and production of water for other uses. Another option follows the "avoided burden" approach: the impacts of supplying secondary products are directly subtracted from the bifunctional scenario, crediting the avoided burden of the process, which would supply the secondary product in a reference system. System expansion was considered by ten studies [17,19,24,26,27,31,32,61,67,68] while substitution by eleven studies [8,14,20,23,25,41–43,48,53,60]. Multi-functionality is generally not considered or clearly stated in the remaining LCA studies.

The functional unit represents the quantification of the functions of the systems under investigation. It is of great importance in any LCA because it serves as the basis for comparison between different systems and further methodological choices such as the definition of system boundaries. Table 1 shows the most common functional units used in previous studies. The common functional unit analyzed (n = 34 studies) is volume-based, i.e., the volume of water treated or reused, which is correct from a methodological point of view and coherent with the goal of the LCA. Some studies [15,18,22,23,31,39,48,55,65] are concerned with the overall operation of a system over a given period. When the analysis is extended to crop production, functional units refers to area [8,24,28,45,46,62] or 1 kg or a ton of product [26,45,59]. The difference in the functional units complicates the cross-comparison of studies and their effective discussion. In wastewater-related LCA studies, establishing a suitable functional unit can be difficult because (i) wastewater treatment plants are becoming multifunctional (function of a wastewater treatment plant or a resource recovery facility) and (ii) the LCA focus is not only on the potential role of treated wastewater reuse as an alternative source of water supply, but also to assess the impacts of producing wastewater-derived products.

2.5. Impact Assessment Methodologies and Environmental Mechanism

An important point of LCAs is the selection of impact assessment methods in the cycle impact assessment (LCIA) stage. The potential environmental impacts from emissions and resource use that can be attributed to specific products in LCAs can be performed by using different impact assessment methods. The method selected and the particulars thereof may influence the results obtained. ReCiPe (n = 24) and the Center of Environmental Science at Leiden University (CML, n = 9) are the most widely used LCIA methodologies to assess environmental impacts, having been selected in thirty-two studies (Figure 2). The ReCiPe method is mainly applied in European context [23,31,39,42,44,50,53,54,57,63,65,71]. The CML method was used in research carried out in the Middle East [47], Asia [17,20,35,37], and Europe [16,51,56,66]. ReCiPe has 18 midpoint environmental impact categories while CML 2000 has 10 environmental impact categories, and both can be applied on a global scale. TRACI is mainly applied in the American context [19,29,39,44]. Six studies [15,21,32,58,60,65] selected Eco-indicator 95/99, five studies [8,26,32,41,57] IPCC, five studies [30,34,40,57,61] Impact 2002+/World+, three studies ILCD [24,49,57] and two environmental footprint method [13,46]. The Cumulative Energy Demand (CED) was applied in five studies [16,32,53,55,57] to estimate the total primary energy consumption. AWARE (Available Water Remaining), a consensus-based method development to assess water use in LCA, is applied in three studies [22,26,53]. It is recommended that an LCA study should apply at least two LCIA methods to check the importance of their choice on the results, such as through the use of sensitivity analysis. Very few studies [8,13,25,26,57,66] applied more than one LCIA method to understand if the use of different LCIA methods may lead to different conclusions.

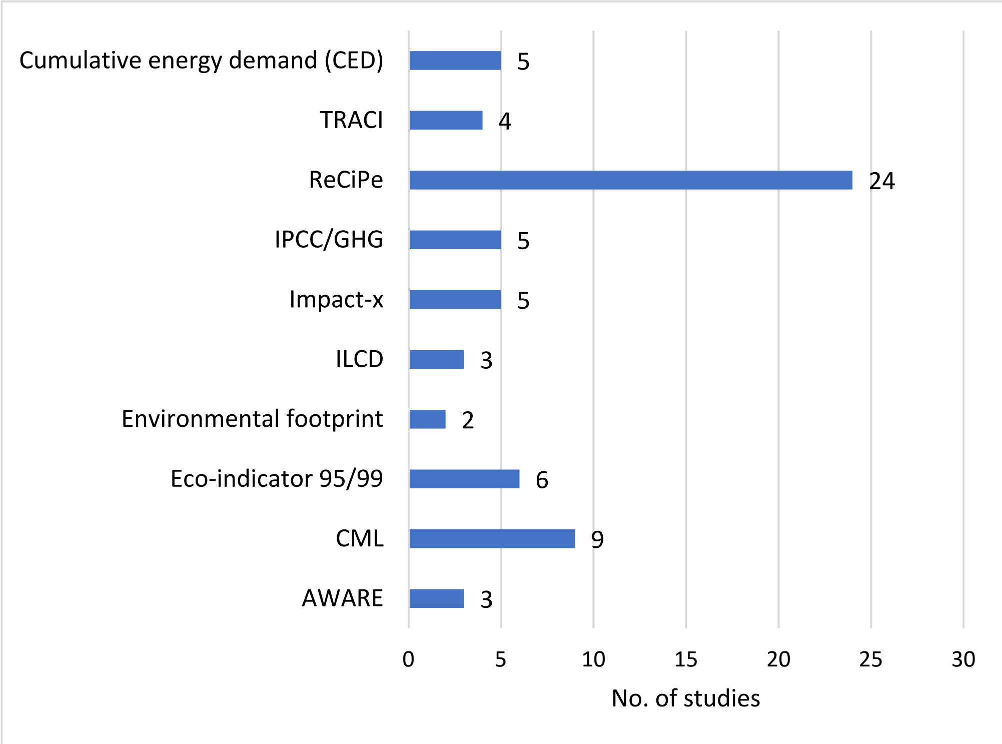


Figure 2. Frequency and type of LCIA method used in LCA studies on wastewater treatment and reuse including irrigation as a process or scenario.

Life cycle impact assessment (LCIA) results are typically calculated through two main approaches: midpoint and/or endpoint. Midpoints are considered to be links in the cause–effect chain (an environmental mechanism) of an impact category, before the endpoints, at which characterization factors or indicators can be derived to reflect the relative importance of emissions or extractions. Common examples of midpoint characterization factors include acidification, eutrophication, ozone depletion, global warming, and photochemical ozone (smog) creation potentials. The endpoint indicators, on the other hand, are further down the chain and relate to the actual damage that those substances, emitted or consumed, can cause (e.g., damage to human health, natural environment and damage to resources). A midpoint assessment was performed in 49 studies (70%), while an endpoint assessment was performed in 21 studies (30%), either separately or in combination with midpoint (Figure 3).

The greater the number of impact categories analyzed, the more comprehensive the description of the environmental profile of products. In the studies reviewed, the number of indicators ranged from a minimum of 1 presented as a single score to a maximum of 21. Azeb et al. [45], Canaj et al. [13], Lane et al. [48], Carre et al. [33], Arzate et al. [25], Roman and Brennan. [30], and Estevez et al. [68] are examples of multi-indicator assessment studies. Global warming potential, also referred to as carbon footprint or impact on climate change, was the most commonly studied impact assessment category (Figure 4), reported in 80% of studies (n = 47). Other common impact categories in LCA studies are eutrophication potential (35 studies or 60%) and acidification (34 studies or 58%). Water-related indicators (water consumption, water depletion, or water footprint) were included only in 34% of the studies (Figure 4). Human toxicity was reported in 26 studies (44%), while eco-toxicities were reported in 28 studies (47%). Energy was reported in nine studies, while land occupation was reported in 7 studies (13%). LCA of water systems must consider carefully the choice of impact assessment models [72], and LCA indicators need to be adapted to the specific local context in which the wastewater treatment plant is embedded [42].

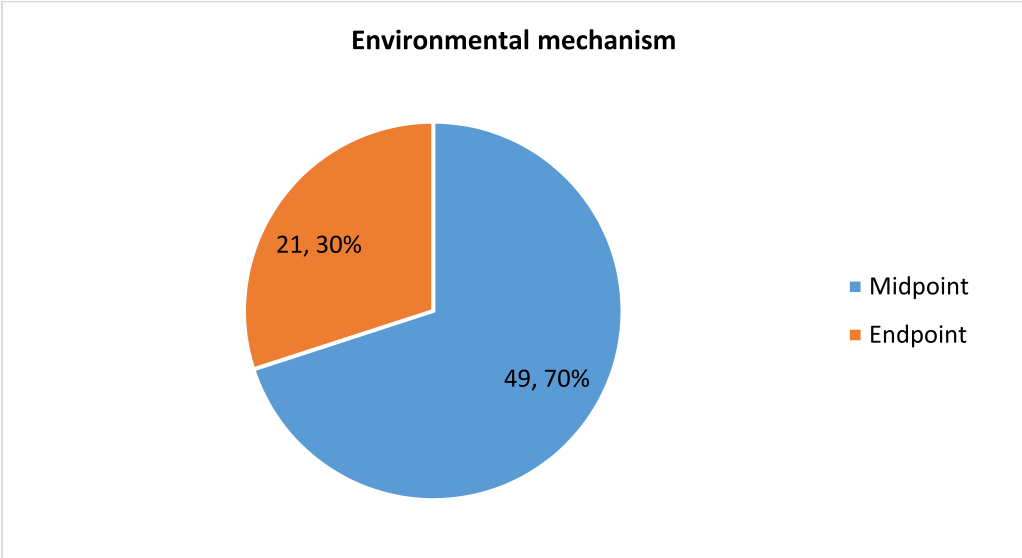


Figure 3. Frequency and type of the environmental mechanism used in LCA studies on wastewater treatment and reuse including irrigation as a process or scenario.

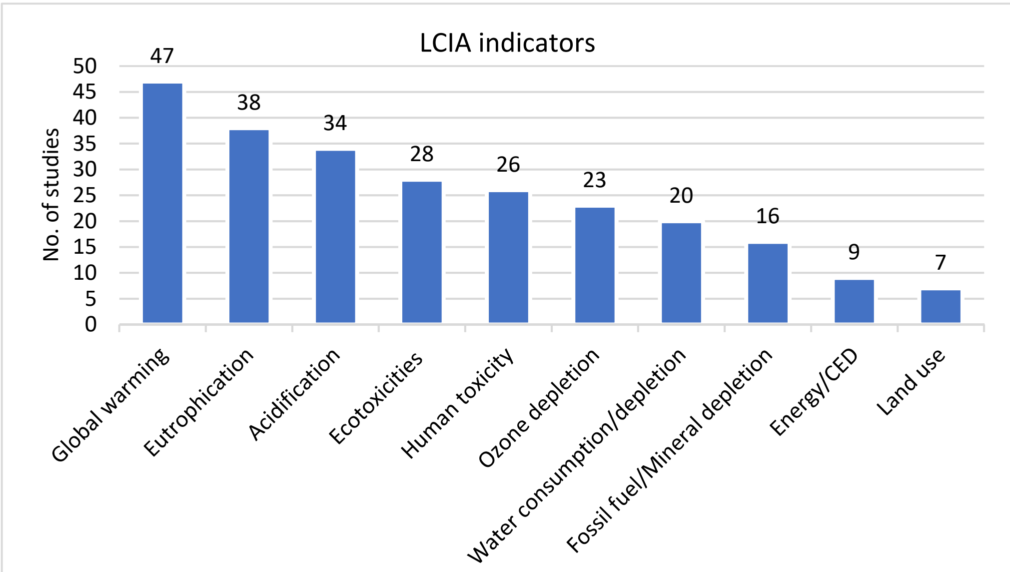


Figure 4. Frequency and type of environmental indicators used in LCA studies on wastewater treatment and reuse including irrigation as a process or scenario.

2.6. LCA Tools and Databases

To model the analyzed systems and technologies, different software tools were used by practitioners. Analyzing the distribution of the software used in the reviewed studies (Figure 5), it is observed that several studies used generic LCA software such as SimaPro (47%), GaBi (14%) and OpenLCA (12%). In 22% (n = 14) of the studies (see Table 1), the LCA software was not specified. Forty-seven (80%) studies used Ecoinvent as a background database, three used GaBi, while nine studies did not specify which database was used.

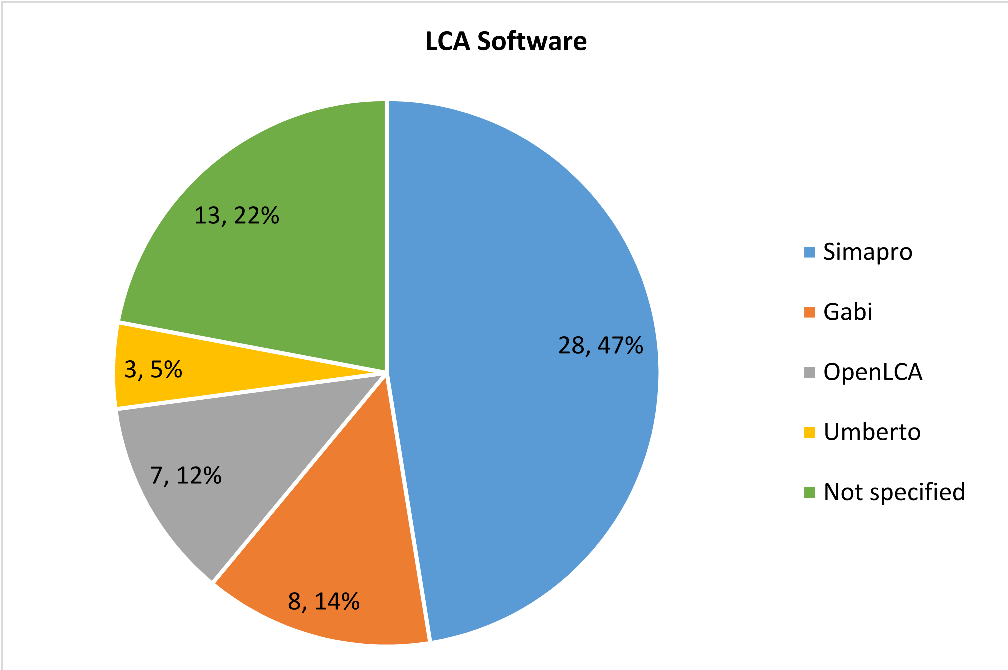


Figure 5. Frequency and type of software considered in LCA studies on wastewater treatment and reuse including irrigation as a process or scenario.

2.7. Uncertainty Consideration

The inclusion of sensitivity analyses in the LCA was also noted (Figure 6). Several authors address uncertainty with sensitivity analyses to account for parameter variation. Around 30 studies (51%) utilized sensitivity analyses to test the impact of changing variables and conditions. The most used approach in the studies is one at a time (moving one input variable, keeping others at their baseline nominal values). This sensitivity analysis is applied in twenty studies [8,13,15,17,23,24,28,29,32,39,41,49,53,55–57,61,64,66,68]. The Monte Carlo method is applied only in ten studies [12,19,26,29,30,38,43,44,46,60].

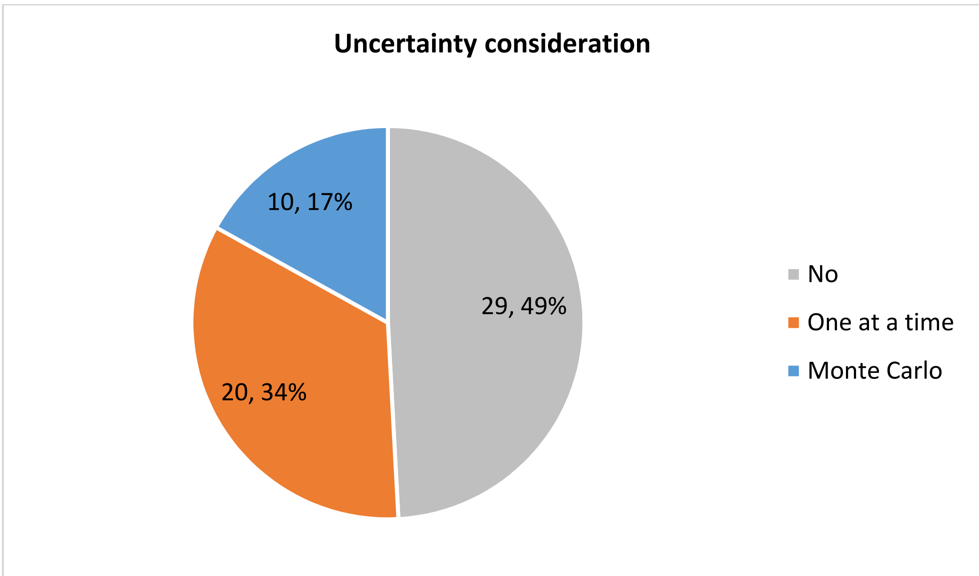


Figure 6. Frequency of uncertainty consideration and their type in LCA studies on wastewater treatment and reuse including irrigation.

3. Discussion and Concluding Remarks

Worldwide wastewater reuse for irrigation is increasingly more practiced. Water reuse strategies are intended as a sustainable way of addressing water scarcity and preventing water pollution [7]. Irrigating crops with reclaimed water is in principle an environmentally friendly practice, as it saves freshwater resources [13,25,26] and promotes the quality of freshwater resources [13,20,26]. Nevertheless, reuse is not always beneficial to the environment as it may involve a relevant contribution to terrestrial ecotoxicity, as compared to a crop using desalinated water and groundwater [27]. The environmental impact of irrigation using reclaimed water can be greater than using groundwater mainly due to excessive fertilization [45] or affected by the wastewater treatment phase [26]. Life cycle assessment (LCA) has been widely used to quantify environmental impacts associated with urban water infrastructure, including wastewater treatment plants (WWTPs) and reuse for irrigation. The main goal of this study was to systematically review the LCA literature to identify the current state of research studies and aid as a starting point for any future research. Our review finds that:

- The environmental impacts of WWTP and reuse for irrigation have been increasingly assessed since 2016, with Europe as the most examined continent and Africa mostly neglected. The importance of LCA as a method for analyzing the environmental performance of products and services from a holistic standpoint is widely recognized in Europe. It is found that the number of LCA researchers based in Africa is still limited, and it appears important for the continent to prioritize education and training regarding life cycle concepts [73].
- The application of LCA research is mainly based on a process perspective, mainly accounting for the design and operation of a wastewater treatment plant for irrigation. Yet, the life cycle environmental impacts of applying these recovered products (water, nutrients, energy, etc.) to irrigated agriculture and examining associated benefits and tradeoffs are generally lacking.
- The boundaries of the systems have not been comprehensively evaluated as the infrastructure and end-of-life have often been neglected. LCA studies [13,26,33,38,48,52,53] have highlighted that energy consumption remains the main contributor to environmental impacts; thus, the type of energy supplied to the product's life cycle will determine the environmental efficiency of reclaimed water [44]. The use of fossil-based electricity contributes to the increase in overall impacts [18] while increasing renewable energies in the electric mix can help to reduce environmental impacts [13,14,16]. Environmental impact from treated effluent and heavy metal emissions as well as manufacturing of systems can be important depending on the water quality and nature of the materials used. It should be noted that the construction phase is expected to increase in significance as the electricity grid moves to a more renewable energy supply through time [44]. Therefore, the integration of multiple environmental impacts is needed to avoid burden shifting and to explore potential tradeoffs between different processes, stages, and indicators.
- Adopted functional units are highly heterogeneous across the revised studies, with volume-based units predominating. Conducting an LCA using multiple functional units can enable a more holistic understanding of the environmental impacts of resource recovery and application.
- The LCA research on irrigation has relied on a limited number of indicators, mainly focusing on global warming, acidification, and eutrophication, while in some emerging studies arrays of environmental indicators have been used. Special attention should be given to the evaluation of other environmental impacts (e.g., water consumption, toxicity, particulate matter, ionizing radiation, photochemical ozone formation, etc.) in addition to the traditional ones. By applying a multi-indicator priorities and trade-offs can be identified.
- Comparison among impact assessment results is a challenge as different methods were used to address the impact assessment. The results showed that ReCiPe and CML are

widely used. The inconsistency caused by different LCIA methods is a long-term challenge for the LCA community. Most of the research applied a midpoint perspective to identify environmental "hotspots" and possible opportunities for improvement across its life cycle. Nevertheless, communication of these LCA results remains a challenge beyond the LCA practitioners as midpoints require at least some knowledge of the multitude of environmental effects to properly interpret the results. The inclusion of both midpoint and endpoint methodologies could provide useful information for different stakeholders. Since sensitivity analysis in combination with uncertainty analysis is insufficient in the current studies, more frequent and comprehensive reporting of uncertainty analysis is recommended.

- Wastewater reuse is an area expected to experience considerable growth in the forthcoming years. Consequently, this would lead to a surge in the demand for LCA in the context of strategic planning and decision-making. The use of life cycle assessment (LCA) is already well developed in the water and wastewater industry [74], but further research is required to ascertain the environmental consequences and to provide scientific guidance for the sustainable utilization of reclaimed water at the farm-level [8]. Our findings highlight that more holistic studies that take into account the expansion of system boundaries, multiple functional units, and the use of a broad set of environmental impact categories, supported by uncertainty and/or sensitivity analysis, are required. Other tools such as risk assessment, life cycle costing, and social life cycle assessment should be evaluated simultaneously when exploring life cycle sustainability of wastewater treatment and reuse.

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