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# 1 Life cycle assessment as decision support tool for 2 water reuse in agriculture irrigation

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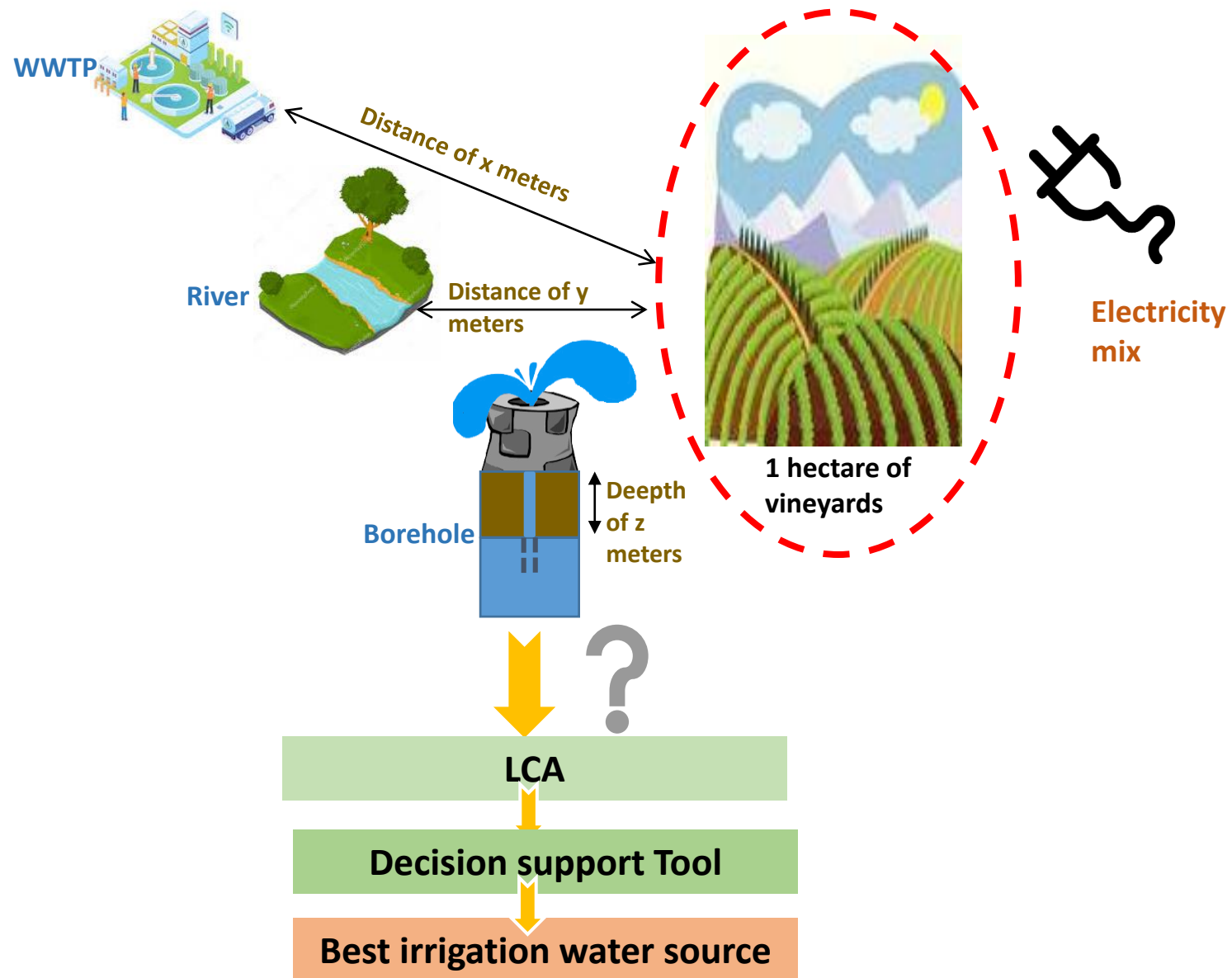
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## 19 **Abstract:**

20 This study presents a decision support tool that evaluates the environmental efficiency of reusing  
21 treated wastewater for agricultural irrigation, among other options. The developed tool is published  
22 as open source at <https://doi.org/10.18167/DVN1/YLP1BA>. The objective of this decision support tool  
23 is to facilitate the interpretation of the Life Cycle Assessment (LCA) results by progressively reducing  
24 the non-discriminatory impacts to solve the difficulty of making a decision with a large number of  
25 criteria. This framework was applied to a representative case of reuse of reclaimed water for vine  
26 irrigation at the Murviel-Les-Montpellier experimental site (Hérault, France). It was then generalized  
27 through modeling assumptions to consider different reuse scenarios.

# When Can Recycled Water Benefit Us?



28 To highlight situations in which the supply of recycled water for irrigation may or may not provide  
29 significant environmental benefits, four main parameters were varied: (i) tertiary treatment  
30 technologies, (ii) availability of conventional water sources, (iii) energy mix composition.

31 The results show that the environmental impact of treated wastewater reuse depends directly on  
32 the type of tertiary treatment technology and the location of the treatment plant in relation to the field  
33 and other water sources. The decision support tool has identified where wastewater reuse is clearly  
34 an environmentally beneficial source of irrigation among surface and groundwater sources (e.g.,  
35 WWTP closer to field than river, groundwater too deep, tertiary treatment environmentally beneficial).  
36 However, there are many situations where the decision support process cannot distinguish between  
37 reuse of treated wastewater for agricultural irrigation and conventional water sources, especially when  
38 the nutrient content of treated municipal wastewater is insufficient to offset the negative effects of high  
39 energy requirements and chemicals of tertiary treatment.

40 **Keywords:** environmental assessment; public decision support; reuse, irrigation, water sources,  
41 agriculture

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### 43 1. Introduction

44 Agricultural production is highly dependent on water and increasingly subject to water risks.  
45 Indeed, irrigated agriculture is the largest user of water in the world. Globally, about 70% of freshwater  
46 resources are consumed for crop irrigation [1]. By 2050, irrigated food production is expected to  
47 increase by more than 50% due to population growth [1]. However, freshwater resources continue to  
48 decline due to climate change, groundwater pollution, and aquifer salinization.

49 In the context of water scarcity, agriculture plays an important role in sustainable management  
50 of freshwater resources and mobilization of alternative water such as treated wastewater and  
51 desalinated water. Reclaimed water is a key alternative water source that has the advantage of being  
52 available most of the time, especially during drought periods [2]. Moreover, the nutrient content  
53 (nitrogen and phosphorous) in reclaimed water can reduce the use of chemical fertilizers and enhance  
54 crop productivity [3]. Reclaimed water reuse in agriculture is a common practice in the Mediterranean  
55 countries and other arid and semi-arid regions where freshwater resources are scarce [3, 4]. For  
56 example, in Italy and Spain, between 8 and 12% of treated municipal wastewater is reused for

57 irrigation [5]. In Tunisia, reuse of treated water for agricultural purposes is promoted by the  
58 government and accounts for 20% of wastewater effluents [6].

59 While reclaimed wastewater reuse has benefits for environmental sustainability, it also poses  
60 risks [3]. In this context, Life Cycle Assessment (LCA) provides a quantitative multicriteria approach  
61 to evaluate the environmental performance of processes throughout their life cycle. Numerous LCA  
62 studies have been conducted to evaluate the environmental impacts caused by either wastewater  
63 treatment systems [7,8] or by crop systems irrigated conventional water [9-12]. However, few evaluate  
64 the environmental impacts of total crop systems irrigated with reclaimed water. Recently, Romeiko [9]  
65 investigated the impact of irrigating corn, soybean, and wheat crops systems with reclaimed and ground  
66 water sources in northern China. Wastewater was treated by biological processes (anaerobic-anoxic-oxic)  
67 followed by chlorine disinfection prior to discharge. The author uses a combination of experimental  
68 measurements and modeling datasets to reflect the specific regional conditions of the study, and he  
69 considers 1 kg of grain as a functional unit (FU). Compared to groundwater resources, reuse showed to  
70 be beneficial for the majority of the environmental impacts, such as global warming, acidification, ozone  
71 depletion, and harmful for non-cancer impacts. Likewise, Moretti et al. [11], based on experimental data of  
72 field work, compared the environmental performance of nectarine orchards irrigated in the Mediterranean  
73 coastal region by two different water sources: (i) treated municipal wastewater by membrane filtration and,  
74 (ii) surface water. The functional unit used is "1 kg of nectarines". The authors found that replacing  
75 groundwater with reclaimed water limited eutrophication. However, reuse performed worse for climate  
76 change, humans and freshwater toxicity mainly affected by the wastewater treatment phase. Miller-Robbie  
77 et al. [12] evaluated greenhouse gas (GHG) emissions and energy use of spinach crop systems in an  
78 Indian urban farm irrigated with three water qualities: Groundwater, untreated wastewater, and treated  
79 wastewater. It was showed that reuse in agriculture can reduce GHG emissions. Rodriguez-Garcia et  
80 al.[13] evaluated assessed the eutrophication and global warming impacts of six different typologies of  
81 WasteWater Treatment Plants (WWTP) coupled with different treated wastewater reuse scenarios  
82 (agriculture, industrial, groundwater recharge, etc.). The plants that reuse treated wastewater for irrigation  
83 include tertiary treatments (UV disinfection or filtration process). The authors used two different functional  
84 units, one based on volume ( $m^3$ ) and the other on eutrophication reduction ( $kg PO_4^{3-}$  removed). The results  
85 of the two FU were different. For the volumetric FU ( $m^3$ ), the results showed that the potential  
86 eutrophication of agricultural reuse is worse compared to the other scenarios, while it seems to be  
87 beneficial for Global Warming Potential (GWP) compared to the acquifer recharge. The study by Meneses  
88 et al. [14] compared the environmental impacts of producing, for irrigation purposes,  $1m^3$  of : non-potable

89 water (for agricultural irrigation and urban uses), potable water and desalinated water. Actual operational  
90 data from a WWTP in the Mediterranean region were used. The results showed that the agricultural reuse  
91 is the most environmentally friendly option, as it reduces the use of fertilizers and thus the energy  
92 consumption for their production. Similarly, Muñoz et al. [15] studied the life cycle impacts of tobacco in  
93 Spain irrigated with three different water sources including groundwater, treated municipal wastewater,  
94 and desalinated water. They found that irrigation with reclaimed water offered potential environmental  
95 benefits, compared to the use of desalinated water, especially in terms of eutrophication, aquatic  
96 ecotoxicity and energy use. In the same vein, Azeb et al. [16] analyzed the impact of irrigation with recycled  
97 water and farmers' practices in greenhouse cucumber cultivation. Compared to groundwater irrigation, the  
98 results show that fertilizers have the highest impact on life cycle analysis in the case of reused water. The  
99 authors explain this by the fact that farmers do not use the optimal fertilizer doses in terms of irrigation  
100 water quality.

101 Moreover, among other options, the environmental efficiency of reclaimed water reuse depends on the  
102 water-energy nexus, which links local water availability to water treatment impacts (as shown by Maesele  
103 et al. [17]).

104 These studies [9, 11-16] provided important outcomes that allow a better understanding of the potential  
105 benefits and main sources of environmental damage from reuse of treated water in agriculture. However,  
106 the results depend on the location and characteristics of the experimental field. There is still a lack of a  
107 broad and systematic overview of the potential environmental impacts of reclaimed water reuse in  
108 irrigation, including the following aspects: Wastewater treatment technologies, fertilizers reduction, water  
109 availability, distance between the WWTP and the field, and energy mix.

110 The objective of this study is to enhance this knowledge and to highlight the environmental trade-offs  
111 between conventional and recycled water as an irrigation source. LCA and decision rules were used in this  
112 work to develop an intelligent tool to support decision making for the appropriate irrigation water source  
113 depending on the context. The entire system of reuse in agriculture is considered: from wastewater  
114 treatment to crop irrigation.

## 115 **2. Materials and Methods**

116 The methodology of LCA is normalized according to ISO 14040. It is an iterative four-stage process:  
117 (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation.

### 118 **2.1. Goal and scope definition**

119 The objective of this study is to introduce LCA as an analytical tool to identify the conditions under  
120 which reclaimed water reuse for irrigation is environmentally efficient. Therefore, we compare a  
121 reference situation in which reclaimed water was used to irrigate the vineyard (scenario #1) in the  
122 experimental platform of Murviel-Les-Montpellier (Hérault, France) with two other virtual irrigation  
123 options: River water (Scenario #2) and Groundwater (Scenario #3), as described below and in Figure  
124 1:

- 125 • Scenario #1: Municipal wastewater is treated by a lagoon and tertiary treatment. The treated  
126 wastewater is reused for vine irrigation from June to September. For the rest of the year, the  
127 wastewater is treated only in the lagoon and discharged into the river. The crop system  
128 irrigated by reclaimed water at the agricultural experimental station in Murviel-Les-Montpellier,  
129 Hérault, France (see below) was used as a representative case study.
- 130 • Scenario #2: River water is used to irrigate the vines in summer (from June to September).  
131 Nevertheless, the wastewater is treated in the lagoon throughout the year and discharged  
132 into the natural environment.
- 133 • Scenario #3: The vines are irrigated with groundwater from June to September and, in  
134 parallel, the wastewater is treated in the lagoon throughout the year before being discharged  
135 into the natural environment.

136 In LCA, the functional unit aims to provide a reference for comparison. In our study, 1 ha of vineyards  
137 is used as a functional unit to compare the environmental impacts of different irrigation scenarios. We  
138 did not use mass-based functional units as used in previous agriculture LCA studies because this  
139 study did not aim to identify the water source that maximizes yield, but to compile and evaluate the  
140 environmental consequences of different water sources used to irrigate 1 ha of vines.

141 The lagoon treatment plant was excluded from the system boundary (Figure 1) because the lagoon  
142 treatment plant was operated regardless of whether its effluent was used for irrigation. In order to be  
143 reused for irrigation (Scenario #1), the lagoon discharge undergoes tertiary treatment. In addition, the  
144 same amount of water was used for all scenarios: 500 m<sup>3</sup>/ ha/ production cycle. However, the impact  
145 of avoided discharge of treated wastewater to the sea was considered in the reuse scenario (Scenario  
146 #1).

## 147 **2.2. General description of the field experiment**

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(a)

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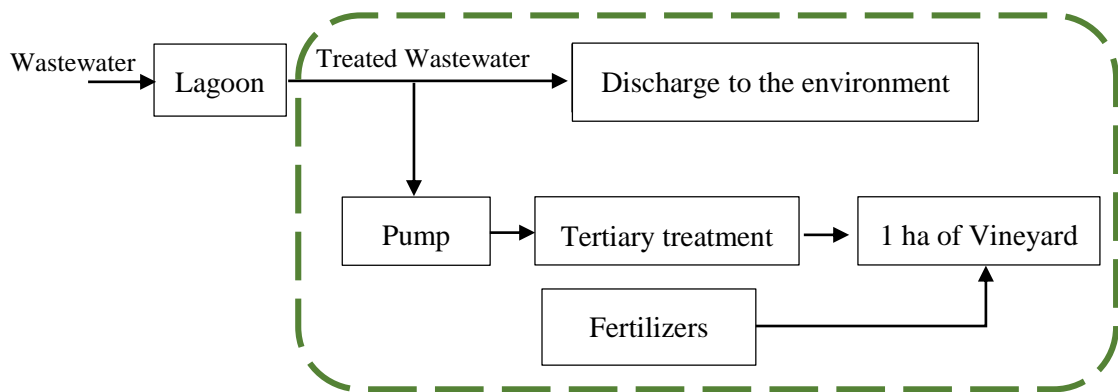
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(b)

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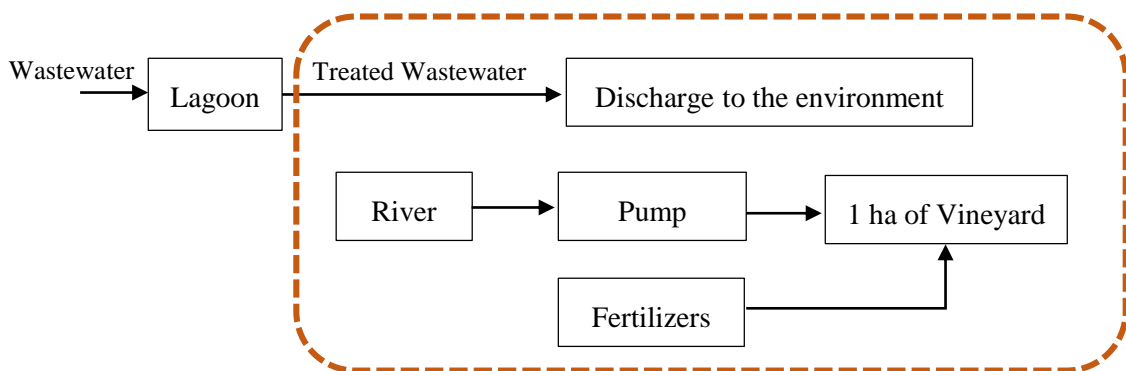
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(c)

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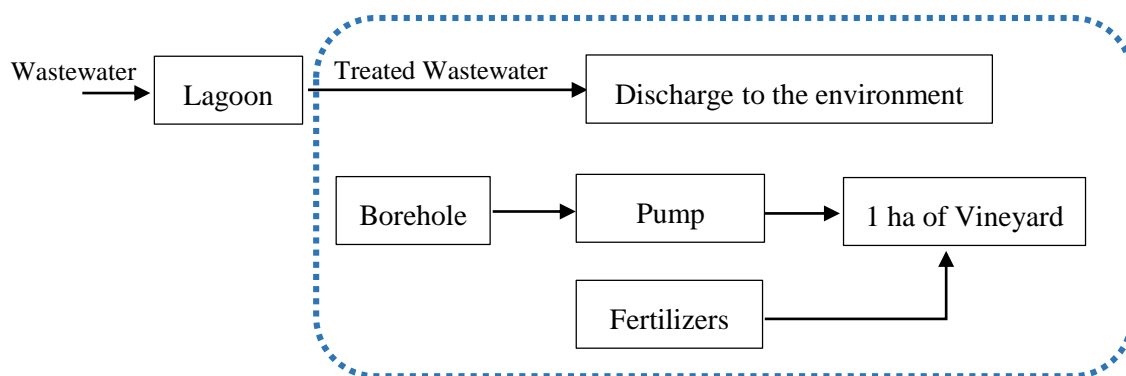
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**Figure 1.**Systems boundaries studied (a) Scenario #1: reclaimed water treatment and reuse for vine

171

irrigation. Part of the treated wastewater is discharged to the environment (b) Scenario #2: Irrigation of

172

vines with river water and discharge of the reclaimed water to the environment (c) Scenario #3:

173

Groundwater irrigation of vines and discharge of the treated wastewater to the environment.

174

The study is based on the experimental work carried out on the experimental platform of Murviel-Les-

175

Montpellier (Hérault, France). This case study is the reference situation in the LCA analysis where

176

reclaimed water is reused in agriculture irrigation. The experimental platform consists of (i) a lagoon

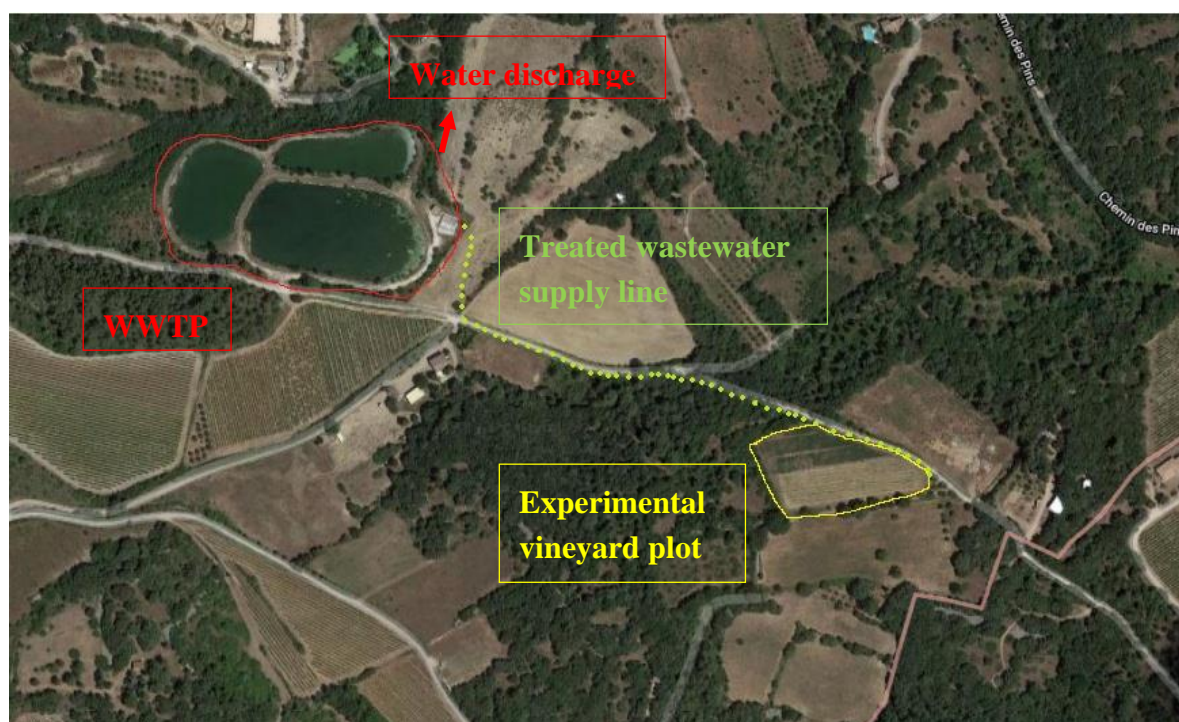
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treatment plant with tertiary treatment composed of a sand filter and UV disinfection, (ii) a 0.5 ha



178 cultivated area with young vines located 600 m from the treatment plant. The plant serves a population  
 179 of about 1500 inhabitants. In 2017, this plant treated about  $200 \text{ m}^3 \cdot \text{d}^{-1}$  ( $73000 \text{ m}^3 \cdot \text{year}^{-1}$ ) wastewater  
 180 from urban collectors. The cultivation area was arranged in 4 rows of 50 m each with 200 vines. The  
 181 spacing between rows was 2 m and the distance between plants was 1 m. Figure 2 depicts the  
 182 location of the experimental platform.

183



184

185 **Figure 2.** Experimental platform for the reuse of treated wastewater for the irrigation of vineyards,  
 186 “Murviel-lès-Montpellier”, Hérault.

187

188

189 Irrigation is carried out from June to September by drip irrigation in accordance with the Decree of 25  
 190 June 2014 amending the Decree of 2 August 2010 on the use of water from urban wastewater  
 191 treatment for crop irrigation. In the off-season, treated wastewater is discharged into the nearest river  
 192 to the experimental site (see Figure 2). Water samples were collected monthly to analyze the  
 193 composition in terms of Biochemical Oxygen Demand (BOD<sub>5</sub>), Chemical Oxygen Demand (COD),  
 194 Total Suspended Solids (TSS), total phosphorus, nitrogen: Total nitrogen, Total Nitrogen Kjeldahl  
 195 (TKN), ammonium ( $\text{NH}_4^+$ ), Nitrogen dioxide ( $\text{NO}_2$ ), nitrate ( $\text{NO}_3$ ). Table 1 shows the average  
 196 composition of the waste water and the reclaimed water for the year 2017.

197

**Table 1.** Average data of the physico-chemical water quality at the inlet and outlet of the WWTP

<b>Water Quality</b>	<b>Waste water (g.m<sup>-3</sup>)</b>	<b>Reclaimed Water (g.m<sup>-3</sup>)</b>
BOD5	302.8	37.5
COD	689,7	171,4
TSS	284	57.8
Total phosphorus	10.3	5.8
Total nitrogen	102.4	41
Total Nitrogen Kjeldahl	102.37	39.4
$NH_4^+$	74.9	29.9
$NO_2$	0.04	0.03
$NO_3$	0.33	0.29

198

### 199 **2.3. Sensitivity analysis**

200 The objective of the sensitive analysis is to assess the impact of the variation of certain parameters  
 201 on the decision making about the irrigation source. Among the key parameters, we selected: (i) tertiary  
 202 wastewater treatment technology, (ii) electricity energy mix and, (iii) geographic context (distance  
 203 between the field and WWTP for Scenario #1, distance between the field and the river for Scenario  
 204 #2; drilling depth for Scenario #3):

- 205 • Tertiary wastewater treatment technology: tertiary treatment is required to ensure that  
 206 reclaimed wastewater meets microbiological standards. Available technologies for  
 207 wastewater reclamation include from simple sand filtration to advanced oxidation processes  
 208 and reverse osmosis. The choice of the most appropriate technology or combination of  
 209 technologies depends on the quality requirements and the expected application of the  
 210 reclaimed wastewater. Three different tertiary treatment processes were investigated in the  
 211 study. The first option is a UV disinfection system. The second option is an UltraFiltration  
 212 (UF) process with two UF membrane lifespans (3 and 5 years). The third option is a  
 213 chlorination system.

- 214 • Electricity production mix: the electricity processes in the ecoinvent database version 3.6 –  
 215 which is included in SimaPro 9.1.1.1 - are specific to the geography. They contain the sources  
 216 for electricity generation, the transmission network, loss due to going between the electricity  
 217 types (e.g. from high to medium voltage), and direct emissions. Ecoinvent specifies the  
 218 geography of the electricity process within the name. This study examines the results for  
 219 different electricity generation mixes in the following countries: France, China, and Spain.
- 220 • Geographic context: to see if the geographic characteristics of the reference case affect the  
 221 results, we performed a sensitivity analysis for the three scenarios compared, as shown in  
 222 Table 2.

223 **Table 2: Geographical contexts parameters considered for the sensitivity analysis**

Scenario	Varied parameter	Value [m]
Scenario #1	Distance between the field and the STEP	100
		1000
		5000
Scenario #2	Distance between the field and the nearest river	100
		1000
		5000
Scenario #3	Drilling depth	30
		70
		110

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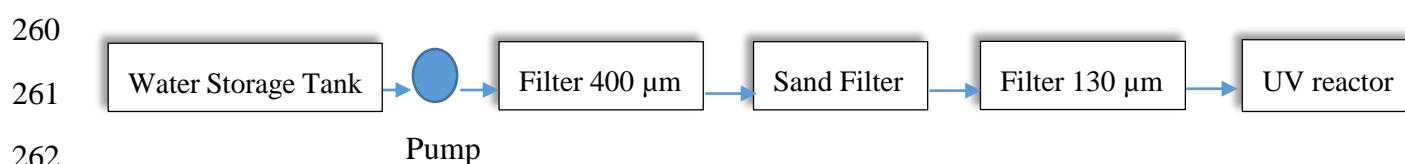
## 225 *2.4. Inventory analysis*

### 226 **Tertiary treatment options**

227 Tertiary treatment becomes increasingly necessary to provide a water quality that conforms to the  
 228 highest standard of French reuse regulations. The following paragraphs describe the different  
 229 modeling assumptions for the tertiary treatment processes under consideration (Figure 3):

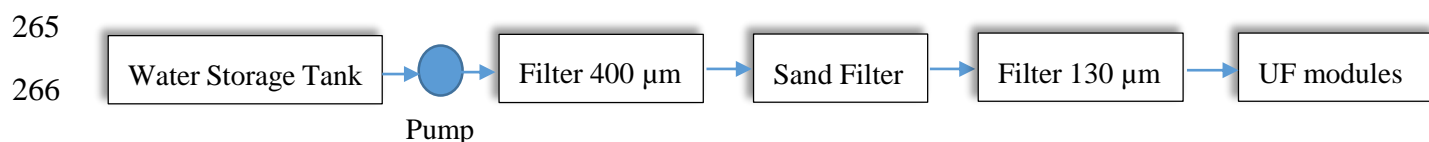
- 230 • UV disinfection: this option includes a disk filter (400  $\mu\text{m}$ ), a sand filter, a disk filter (130  $\mu\text{m}$ )  
231 and an ultraviolet (UV) system. The sand filter weighs 34 kg of steel and it contains a weight  
232 of 330 kg of filter sand. The disk filter (400  $\mu\text{m}$ ) is an Amiad FILTOMAT M100 filter, consisting  
233 of 25 kg of steel. This type of filter has a water-activated self-cleaning mechanism that does  
234 not require an external power source to operate. The modeled UV unit was assumed to be a  
235 single lamp (300 to 750 W) system. The material data for the UV lamp, vessel reactor, quartz  
236 sleeve, sleeve wipers and main electronics were taken from the work of Carré et al. [18]. The  
237 lamps run only during demand for irrigation with a power consumption of about 0,01 kwh/m<sup>3</sup>  
238 [18]. The UV Lamp Life Expectancy is considered to be 10000 hours, according to [19].
- 239 • UF filtration: this option consists of a disk filter (400  $\mu\text{m}$ ), a sand filter, a disk filter (130  $\mu\text{m}$ )  
240 and the UF pilot AQUAMEM UF80-12. The sand filter and the disk filter are the same as in  
241 the option 1 (UV disinfection). The AQUAMEM UF pilot consists of 12 modules, which contain  
242 hollow fibers made of polyethersulfone, accounting for a total surface area of 42 m<sup>2</sup> per  
243 module. Each fiber has a porosity of 0.01 $\mu\text{m}$ . The maximum admissible water flow in the UF  
244 pilot is 25 m<sup>3</sup>/h. It is assumed that 20% of the pilot plant power consumption is used in  
245 hydraulic membrane backwash and chemical wash is negligible.
- 246 • Chlorination: the chlorine disinfection alternatives includes a disk filter (400  $\mu\text{m}$ ), a sand filter,  
247 a disk filter (130  $\mu\text{m}$ ), a 10 m<sup>3</sup> chlorine contact basin where the sodium hypochlorite is added  
248 to the water and allowed to contact the contaminants for 30 minutes, a 2 m<sup>3</sup> chlorine tank,  
249 and a metering pump to inject the chlorine from the chlorine tank into the contact basin.. The  
250 amount of process material, sodium hypochlorite, and energy consumption was quantified  
251 using the equations and information given in [19]. The chlorine storage tank is made of  
252 propylene and the chlorine contact basin is made of concert.
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259 **UV disinfection**



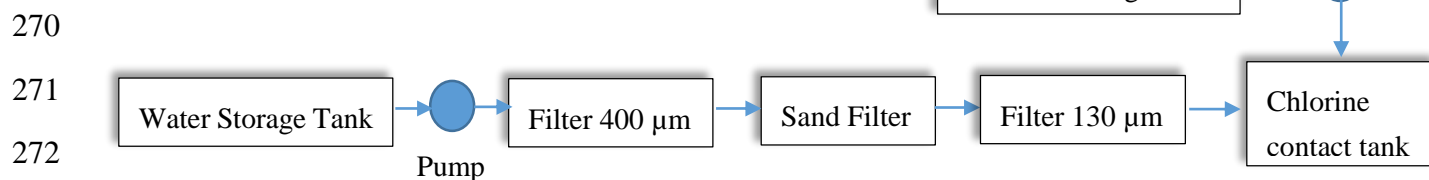
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264 **UF Filtration**



268

269 **Chlorination**



274 **Figure 3.** Individual components of the three investigated tertiary treatment scenarios: tertiary  
 275 treatment with UV disinfection, tertiary treatment with UF filtration and tertiary treatment with  
 276 chlorination.

277

278 **Infrastructure water transport**

279 The infrastructure for water transport from the source to the field consists of: (i) a centrifuge pump  
 280 and (ii) PVC pipes for water transport from the water source to the field and (iii) ) PVC pipes for field  
 281 irrigation.

282 The field irrigation system is excluded, as the same crop system was considered in the different  
 283 scenarios. However, the pump characteristics and the length of the transport pipes depend on the  
 284 type of water source and the distance to the field. For scenario #1, the reclaimed water was  
 285 transported via plastic pipes from the adjacent WWTP and stored in a pond. For scenario #2, river  
 286 water was transported via plastic pipes from the adjacent river and used directly for irrigation without  
 287 prior storage. In the scenario #3, groundwater for irrigation was obtained from the on-site groundwater  
 288 well.

289 The water flow rate delivered to the field by the centrifugal pump is fixed at 20 m<sup>3</sup>/h, regardless of the  
 290 type and location of the irrigation water source. The pump must deliver a certain pressure, called the  
 291 total head, which depends on the suction and discharge conditions. In any case, the selection criterion  
 292 for the centrifugal pump is the total head of the system (THS), since the flow rate is the same in the  
 293 field. Following the THS calculations, the Zanni pumps listed in Table 3 were selected for Scenario  
 294 #1 (reuse) and Scenario #2 (surface water):

295 **Table 3: Centrifuge pumps for water feeding for scenario #1 and #2**

River/Field or WWTP/Field distance [m]	Pump Type	Weight [kg]	Efficiency [%]	Life Expectancy [Year]	ecoinvent unit name	LCI process
100	HM 32 A/1	72			Cast iron	
1000	HM 32 A/1	72	57	4	{GLO}  market for	
5000	HM 32 A/2	87			Cut-off, S	

296 For the reuse scenario, centrifugal pump drive the lagoon effluent through tertiary treatment (UV, UF  
 297 or chlorination processes) to the field. For borehole irrigation (scenario #3), the characteristics of the  
 298 GrundFos submersible pump under consideration are summarized in Table 4:

299 **Table 4: submersible pumps for water feeding for scenario #3**

Borehole depth [m]	Pump Type	Weight [kg of cast iron]	Efficiency [%]	Life Expectancy [Year]	ecoinvent unit name	LCI process
30	SP-30-4	31			Cast iron	
70	SP-30-9	62	57	4	{GLO}  market for	Cut-off, S
110	SP-30-15	78				

300

**Fertilization**

302 Since the objective of this work is not to study the contribution of the irrigation water source to  
303 fertilization, the same amount of fertilizer was applied to the crop in the different scenarios. For the  
304 reclaimed water plots, the nutrients came from both fertilizer and reclaimed wastewater. The fertilizer  
305 schedule was designed to meet the nutrient needs of the plants, considering the average annual  
306 chemical properties of the reclaimed water. The same amount of nutrients was applied to the plots  
307 with conventional water (Scenario #2 and #3). Moreover, Scenario #1 has been expanded by  
308 including the impacts generated by the avoided fertilizers production, since reclaimed water irrigation  
309 reduced the requirements of fertilizer.

310 The composition of NPK fertilizer used per ton of product is 6.7 kg of total Nitrogen, 4 kg of  $P_2O_5$  and  
311 12 kg of  $K_2O$ , which corresponds to the theoretical fertilizer requirement of grapevine under similar  
312 conditions as recommended by the French Institute of Vine and Wine. Fertilizer production was  
313 included in the system boundaries because of its impact on agricultural LCA [11]. The impact of  
314 fertilizer application was excluded because it was carried out with the same equipment in different  
315 scenarios. Similarly, pesticide production and application were excluded because it is assumed that  
316 the same amount of pesticide is applied in all scenarios.

**On-field emissions**

318 Irrigation and fertilization of crops causes nitrogen and phosphorus emissions to air, soil, and water.  
319 These emissions must be quantified for LCA analyzes. Quantified nitrogen emissions are root  
320 uptake, volatilization, and leaching. Phosphate emissions are soil erosion, leaching, and runoff.  
321 In the absence of experimental data for emissions to air and groundwater and inconsistent on-site  
322 soil analysis data, these emissions are estimated using mathematical models from the literature.  
323 Nitrogen ( $N_2$ ), ammonia ( $NH_3$ ), nitrous oxides ( $N_2O$ ), nitrate ( $NO_3^-$ ) and nitrogen oxides ( $NO_x$ )  
324 emissions were estimated using models published in the World Food LCA Database [20]. However,  
325 Agribalyse models were used to estimate phosphorus emissions.

**End of life phase**

327 The end-of-life stages for materials systems are modeled using the ecoinvent 3 processes, as shown  
328 in Table 5. The end-of-life phase includes the dismantling of infrastructures (e.g. storage tanks),

329 recycling of steel as it represents a significant portion of the total waste and recycling, while other  
 330 materials such as concrete and PVC are sent to final disposal in landfills and/or municipal incineration  
 331 (e.g., plastics). In our case study, the recycling of plastics was not taken into account, as only a small  
 332 proportion of plastic waste is recycled in France (< 20%) [18].

333

334

**Table 5: end-of-life stages for materials systems**

Material	Used by	End of life (ecoinvent LCI unit process)
Concrete	chlorine contact tank; Water storage tank	Waste concrete {Europe without Switzerland}  market for waste concrete   Cut-off, S
PVC	PVC pipes for water transport from the water source to the field	Waste polyvinylchloride product {Europe without Switzerland}  market for waste polyvinylchloride product   Cut-off, S
Polypropylene	Chlorine storage tank	Waste polypropylene {Europe without Switzerland}  market group for waste polypropylene   Cut-off, S
Steel and iron	Sand filter; Disk filter; Storage Tank; Pumps; UV reactor; UF pilot	Steel and iron (waste treatment) {GLO}  recycling of steel and iron   Cut-off, S
Sand	Sand filter	Inert waste {Europe without Switzerland}  market for inert waste   Cut-off, S

335

**3. Calculation**



### 336           **3.1. LCA Impact analysis**

337   LCA requires the processing, calculation and analysis of a wide range of information. The use of LCA  
338   software facilitates these different phases, ensuring transparency and traceability. SimaPro is a  
339   calculation software that links inventory data, informed by the LCA producer, to the environmental  
340   damage caused by the inventoried substances. It was developed by the Dutch and is a world leader  
341   in the implementation of LCA. SimaPro software version 9.1.1.1 integrates several evaluation  
342   methods (Recipe, ILCD, Usetox...) and various life cycle inventory databases (ICV) (ecoinvent, ELCD,  
343   LCA Food). In this work, the method of International Reference Life Cycle Data System (ILCD) 2011  
344   method [21] was selected. This method is recommended by the European Commission, which has  
345   analyzed several methodologies for life-cycle impact assessment to reach a consensus on the  
346   recommended method for each environmental topic, both at midpoint and endpoint levels. Because  
347   each step of the impact analysis generally involves additional assumptions and uncertainties in  
348   characterizing damages, the uncertainty in the results increases as one progresses from the inventory  
349   to mid-point category and then from the mid-point category to the damage results. To limit the  
350   uncertainties, only the midpoint impact categories from the ILCD method were used in this study. In  
351   addition, 8 midpoint impact categories were determined: Climate Change (CC), Ozone Depletion  
352   (ODp), Human Toxicity (HT) that regroup human carcinogenic toxicity and human non-carcinogenic  
353   toxicity, Ionizing Radiation (IR), Acidification (Ac), Freshwater Eutrophication (FEp), Marine  
354   Eutrophication (MEp), Freshwater Ecotoxicity (FEt).

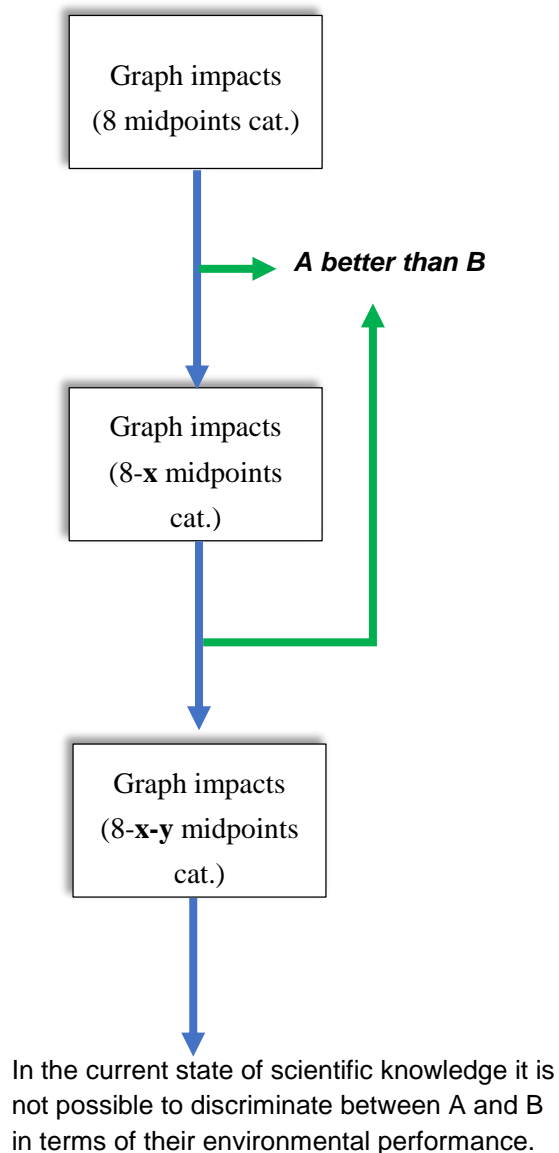
### 355           **3.2. Decision support tool**

356   Typically, the main difficulty among the LCA use is the interpretation of highly multicriteria results.  
357   Indeed, one can conclude that A is better than B only if ALL impacts are lower. Otherwise, it is not  
358   possible to discriminate between A and B from an environmental point of view and other criteria must  
359   be considered. As a consequence, we developed an LCA calculator in excel that includes the selected  
360   LCA impacts categories (the 8 midpoint impact categories) and a simple decision-making procedure  
361   inspired from [22]. This LCA decision support tool is published  
362   under <https://doi.org/10.18167/DVN1/YLP1BA>. It consists in reducing, gradually, the number of  
363   impacts considered by applying elimination rules. In fact, limiting the number of impacts leads to  
364   reduce the complexity of the information transmitted and to guide the decision-maker to a choice.

**Step 1:** conventional impacts graph

**Step 2:** Delete the **x** categories of impacts for which the difference between the two scenarios is low (below an uncertainty threshold of 10% for all categories and 30% for TOX ECOTOX)

**Step 3:** Delete the **y** categories of impacts whose contribution to the single score is low (less than 0,1%)



365

**Figure 4: Decision-support tree for the analysis of the LCA results**

366

After displaying comparison LCA results between two scenarios with SimaPro, we guide decision

367

making according to the decision tree presented in Figure 4. In fact, If the scenario A is not better

368

than scenario B on all the considered impacts, then the first elimination step will be applied

369

automatically by excel. The first elimination step consists in the delete of the **x** categories of impacts

370

for which the difference between the two scenarios is below an uncertainty threshold of 10% for all

371

categories and 30% for TOX ECOTOX. The two uncertainty thresholds for the step 2 (10 and 30%)

372

were used, based on Jolliet et al. [23] While it is not always possible to decide between A and B at

373

the step 2, Excel go to step 3. This last consist on the remove of the **y** categories of impacts whose

374

contribution to the single score is low (less than 0,1%) [23]. If it is still unable to choose between A

375

and B, then we can conclude that in the current state of scientific knowledge it is not possible to

376 discriminate between A and B in terms of their environmental performance. In this case, the decision  
377 can be based on the other components of sustainability (social & economic).

#### 378 **4. Results and Discussion**

379 First, we consider the French electricity mix and compare the environmental impact of irrigation with  
380 reclaimed water and river water for different scenarios: different tertiary treatment and different  
381 distance between field and river and field and STEP. Second, for the same mix and reuse scenarios,  
382 we compare irrigation with reclaimed water and drilling water for different drilling depths. Finally, the  
383 electricity mix is varied to evaluate the impact of the energy source on the choice of the appropriate  
384 irrigation water source.

385 Table 6 shows the results of the Excel calculator based on LCA for the different scenarios assessed,  
386 so that the reader can simultaneously observe the relative impact of the different circumstances on  
387 the irrigation water source decision.

##### 388 **4.1. Reclaimed water VS Surface water for the French mix**

389 Sub-table 6-A presents the comparison LCA results between scenario #1 (irrigation with TWW) and  
390 scenario #2 (surface irrigation) for different tertiary treatments, different geographic contexts  
391 (field/WWTP and field/river distances), and for the French electricity mix.

##### 392 **Table 6: Results of the decision support tool comparing reclaimed water reuse to river irrigation** 393 **(A,C,D) and reclaimed water reuse to borehole irrigation (B,D,F)**

394 *The adjusted parameters are: (i) three tertiary treatments (chlorination, UF filtration with two different membrane life*  
395 *spans of 3 and 5 years, UV disinfection), (ii) three distances between field and WWTP (100 m, 1000 m, 5000 m), (ii) three*  
396 *distances between field and River (100 m, 1000 m, 5000 m) , (iii) three borehole depths (30 m, 70 m, 110 m), (iv) three*  
397 *electricity mixes ( France, China, Spain).*

398 *No conclusion means that, under the considered conditions, the decision-making procedure cannot easily distinguish*  
399 *between the two compared options.*

400 *River means that, under the considered conditions, irrigation with surface water is more environmentally friendly than the*

401 *reuse option.*

402 *Borehole means that, under the given conditions, groundwater irrigation is more environmentally friendly than the reuse*

403 *option.*

404 *Reuse means that, in this situation, supplying reclaimed water for irrigation offers significant environmental benefits.*

**REUSE versus RIVER**

**French mix**

Tertiary treatment		Chloration			UF membrane			UF membrane 5 years			UV		
Field-WWTP distance Field-River distance		100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
(A)	100	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
	1 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
	5 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE

**Chinese mix**

Tertiary treatment		Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Field-River distance		100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
(C)	100	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
	1 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
	5 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE

**Spanish mix**

Tertiary treatment		Chloration			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance Field-River distance		100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
(E)	100	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	No conclusion
	1 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE
	5 000	No conclusion	No conclusion	No conclusion	RIVER	RIVER	RIVER	RIVER	RIVER	RIVER	REUSE	REUSE	REUSE

**REUSE versus Borehole**

**French mix**

Tertiary treatment		Chlorination			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance		100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
Borehole depth													
(B)	30	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	No conclusion
	70	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE
	110	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE

**Chinese mix**

Tertiary treatment		Chlorination			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance		100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
Borehole depth													
(D)	30	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	No conclusion
	70	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE
	110	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE

**Spanish mix**

Tertiary treatment		Chlorination			UF membrane 3 years			UF membrane 5 years			UV		
Field-WWTP distance		100	1 000	5 000	100	1 000	5 000	100	1 000	5 000	100	1 000	5 000
Borehole depth													
(F)	30	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	No conclusion
	70	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE
	110	No conclusion	No conclusion	No conclusion	Borehole	Borehole	Borehole	Borehole	Borehole	Borehole	REUSE	REUSE	REUSE

407

408 ***UV disinfection***

409 Analysis of the results in sub-table 6-A showed that the reuse scenario is more beneficial than  
410 irrigation from surface water (river) only in the case of UV tertiary treatment and when the field is  
411 closer (or at the same distance) to the WWTP than to the river. In the latter cases, scenario #1 with  
412 UV treatment generates lower impacts in all considered impacts categories except acidification where  
413 the difference between the two-compared scenarios is not significant at about 3% (10% is the defined  
414 uncertainty threshold for the percentage of significant difference between two non-toxicity impacts  
415 [22]). For this reason, the choice of the reuse scenario was obvious. In this case, field irrigation with  
416 TWW generates a net benefit resulting from:

- 417 • the avoided discharge of TWW into the environment
- 418 • the replacement of fertilizers with the nutrients provided by TWW
- 419 • the reduction in electricity used to pump the water, since the field is closer to the WWTP than  
420 to the river

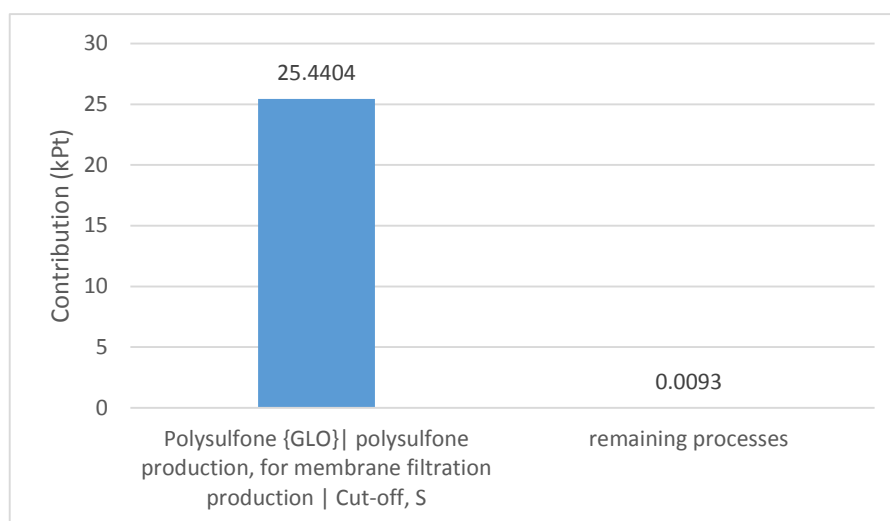
421 ***UF filtration***

422 In this case, the tertiary treatment of the reclaimed water is an ultrafiltration process composed of 12  
423 polysulfone filtration membranes. Based on the decision rules, the environmentally preferred irrigation  
424 scenario in this case is scenario #2: river or surface irrigation (see sub-table 6-A). In fact, the  
425 reclaimed water scenario showed higher life cycle impacts than the surface water scenario,  
426 regardless of the distance of the field from the WWTP and the nearest river (Table 2). Analysis of the  
427 contribution of scenario #1 with UF tertiary treatment shows that the production of polysulfone, the  
428 membrane material, is the largest contributor to the total impact (Figure.5). The other sub-systems  
429 are not shown in the figure, because their contribution to the total environmental impact is small (about  
430 0.04%).

431 Extending the membrane lifespan from three to five years reduces the magnitude of the different  
432 impact categories but does not change the decision. In fact, the surface water source is still better  
433 than reuse with UF tertiary treatment. In addition, it was assumed that there is no chemical cleaning  
434 of the membranes, which could affect the results.

435

436



437

438

**Figure 5: Contribution analysis to the single score of scenario #1 with UF tertiary treatment for a distance of 100 m between the field and the WWTP and a membrane lifetime of 3 years.**

439

#### 440 **Chlorination**

441 If the tertiary treatment is a chlorination train, the decision tool shows that it is not possible to  
 442 distinguish between reuse with chlorination tertiary treatment and surface irrigation (river irrigation) in  
 443 terms of environmental performance. The same trend is observed for all geographical situations  
 444 considered (Table 2). If we look more closely at the results of the impact categories, we can see that  
 445 reuse is the worst option in terms of ozone depletion, acidification and ionizing radiation. The pollutant  
 446 with the greatest contribution to the ozone depletion category is the sodium hypochlorite (NaOCl),  
 447 which is used to disinfect reclaimed water. NaOCl is produced by reacting a dilute caustic soda  
 448 solution with liquid or gaseous chlorine. Ionizing radiation is mainly affected by the energy required  
 449 to pump water followed by NaOCl production. In the same way, hypochlorite production and field  
 450 emissions were most significant in acidification impact categories. However, reclaimed water reuse  
 451 reduces climate change, eutrophication and ecotoxicity impact categories due to avoided fertilizers  
 452 uses and fewer nutrient emissions into the natural environment.

#### 453 **4.2. Reclaimed water VS Drilling water for the French electricity mix**

454 This comparison reflects the situation in which the decision-maker must choose between reclaimed  
 455 water reuse and borehole water irrigation source in different contexts. In this sense, a sensitivity  
 456 analysis was carried out in order to determine the influence of (i) borehole depth, (ii) distance between



457 field and WWTP and, (iii) tertiary treatment of reclaimed water on the outcomes of LCA. As shown in  
458 the sub-table 6-B, these parameters are critical to the choice of irrigation source (reuse or borehole).

#### 459 ***UV disinfection***

460 For UV tertiary treatment, reuse is indeed more environmentally efficient than borehole irrigation,  
461 unless the WWTP is too far from the field (distance  $\geq 5000$  m) and the groundwater is at shallow  
462 depth ( $\leq 30$ m). In this last case, reuse is poor only in IR. It is twice as important as groundwater  
463 irrigation because of the electricity consumption, which contributes in IR impact by 98% in the reuse  
464 case and 90% in the case of groundwater irrigation. In fact, the electrical energy required to transport  
465 the TWW over a distance of 5000 m is higher than that required to pump water from a 30 m deep  
466 borehole. However, when the borehole depth is greater than or equal to 70 m, reuse with UV  
467 treatment is environmentally beneficial because the nutrient content in the TWW reduces the use and  
468 production of fertilizers, mainly affecting CC, ODp, HT, Ac and FEt. For example, when the distance  
469 between the field and the WWTP is 5000 m and the borehole depth is 110 m, the contributions of  
470 fertilizer use in scenario #3 are 70% for CC, 46% for ODp, 80% for HT, 58% for Ac, and 84% for FEt.  
471 The impact of the groundwater irrigation scenario on freshwater and marine eutrophication impacts  
472 is mainly caused by the discharge of lagoon effluent, which is partially avoided in the reuse scenario.

#### 473 ***UF filtration***

474 Based on the results from LCA, the excel calculator decides that is not environmentally friendly to  
475 replace groundwater with TWW for UF tertiary treatment. This is mainly due to the production of  
476 membrane material, which strongly affect all the considered environment categories. Although the  
477 reuse decreases the lagoon emissions, the UF tertiary treatment with its 12 modules of 42 m<sup>2</sup> of  
478 polysulfone per module increases all the environmental impacts of scenario #1 with UF. After  
479 polysulfone production, electricity is the process that has the highest impact on all categories, expect  
480 for marine and freshwater eutrophication, which are affected by emissions from the lagoon. For  
481 marine and freshwater eutrophication, the difference between the two scenarios is not more than  
482 30%, because the amount of recycled wastewater is not very important.

#### 483 ***Chlorination***

484 As in the case of surface irrigation, the decision support tool shows that it is not possible to distinguish  
485 between the two water sources: Reuse with tertiary chlorination and groundwater. Indeed, reuse with  
486 tertiary chlorination reduces climate change, human toxicity, freshwater eutrophication, marine

487 eutrophication, and freshwater ecotoxicity over the life cycle. However, the impact of irrigation with  
488 treated water is twice that of irrigation with groundwater and the life cycle of IR is too important. The  
489 first life cycle impact factor of ODP in the reuse scenario is sodium hypochlorite used for chlorination  
490 of TWW. In addition, no significant difference is found between the two options for freshwater and  
491 seawater eutrophication. Consequently, the decision is up to the decision maker, who could rely on  
492 other indicators to choose between the compared water sources.

#### 493 **4.3. Electricity mix**

494 The same LCA analysis as in sections 4.1. and 4.2. was reproduced, but the French energy mix was  
495 replaced first by the Chinese mix and then by the Spanish mix.

#### 496 **Chinese electricity mix**

497 China is by far the largest producer of electricity from fossil fuels, accounting for nearly 73%. The  
498 results presented in Table 6-C and 6-D show that, the conclusions for the Reuse VS River and Reuse  
499 VS Borehole scenarios remain the same when we replace the French electricity mix with the Chinese  
500 electricity mix. However, analysis of the results from LCA for the last two cases shows that the high  
501 ionizing radiation of the French electricity mix is reduced when it is replaced by the Chinese mix,  
502 which contains a lower proportion of nuclear electricity. However, the climate change, acidification  
503 and ecotoxicity impacts increase because the Chinese electricity mix is mainly generated from fossil  
504 fuels. As stated earlier, these changes do not affect the overall conclusions on the reuse.

#### 505 **Spanish electricity mix**

506 Results from LCA show that replacing the French electricity mix with the Spanish electricity mix would  
507 reduce IR and ODP but increase climate change, acidification and ecotoxicity impacts, because the  
508 Spanish mix contains about 45% fossil energy. However, the difference between the results of the  
509 two mixes (Spanish and French) is observed only for River VS Reuse scenario and when the field is  
510 1000 m from the river and 5000 m from the WWTP. In the latter case, the reuse is ecologically  
511 beneficial, since the Spanish mix reduces considerably its ODP impact compared to river scenario.

### 512 **5. Discussions**

513 The results of the decision support tool has shown that the environmental benefits of agriculture  
514 wastewater reuse over conventional water remain case-by-case dependent and no general

515 conclusion can be drawn. The decision on reuse depends on the characteristics of the treatment  
516 technology, especially tertiary treatment, and the specifics of the site.

517 Tertiary treatment of wastewater is not only a disinfection step, but can also prevent operational  
518 problems due to clogging of drippers with biofilms. However, the complexity of the technology (e.g.,  
519 UF treatment) and the use of chemicals (e.g., chlorination) could increase the environmental impacts  
520 of the reuse scenarios compared to groundwater and surface irrigation. The environmental benefits  
521 of treated wastewater over conventional water sources are related to the reuse of treated wastewater,  
522 which reduces the use of fertilizers. If the wastewater is not reused, it will be discharged into the  
523 aquatic environment where it will affect freshwater and marine eutrophication. Thus, reuse can be a  
524 double-edged sword.

525 Conventional water sources also have negative impacts on the environment through (i) the energy  
526 consumption required to extract and transport water, (ii) emissions from the production and use of  
527 fertilizers and (iii) the release of TWW into the environment. In addition, on the one hand, overuse of  
528 conventional water sources is the cause of water quality (i.e., salinization) and quantity degradation.  
529 On the other hand, surface and groundwater can also be polluted by human activities and wastewater  
530 discharges, which can lead to contamination of water resources by pathogens. The problem is not in  
531 contrast with wastewater treated by tertiary treatment, which is a disinfection step. The consideration  
532 of pathogens in urban water is still relatively complex in LCA, as shown by [24].

533 The aim of this work is to provide decision makers with a tool to decide on the efficiency of reuse  
534 depending on the specifics of the case considered. However, the lack of data on country-specific  
535 water scarcity could affect the accuracy of the results. Endpoint indicators could be used to consider  
536 the impact of water scarcity, as shown in [17]. Thus, decision makers can improve their decisions by  
537 considering water availability at the site in question.

538 In addition, the local electricity mix can also influence the environmental efficiency of TWW reuse.  
539 Likewise, endpoint impact indicators could provide more useful information on the impact of the  
540 energy-water mix than midpoint indicators [17]. The integration of endpoint impacts will be the subject  
541 of our future work to improve the proposed decision tool.

## 542 **6. Conclusions**

543 This paper presents an intelligent decision tool that supports the selection of environmentally friendly  
544 irrigation water source depending on the context. It uses LCA impacts data generated by SimaPro

545 and predefined decision rules programmed in Excel. This tool is available as open source at  
 546 <https://doi.org/10.18167/DVN1/YLP1BA>. The decision support tool identifies the conditions (treatment  
 547 technologies, geographic context, energy mix) under which reuse is environmentally beneficial. In  
 548 some situations, the decision support tool is unable to distinguish between conventional and non-  
 549 conventional irrigation (reuse) from an environmental perspective. This is a first step in facilitating a  
 550 decision maker's use of LCA with respect to reuse efficiency. In addition, other factors (economics,  
 551 regulations, etc.) should be considered.

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 560 discussions.

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