Water Reuse

Water Reuse Vol 13 No 3, 295 doi: 10.2166/wrd.2023.054

Water reuse for vine irrigation: from research to full-scale implementation

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ABSTRACT

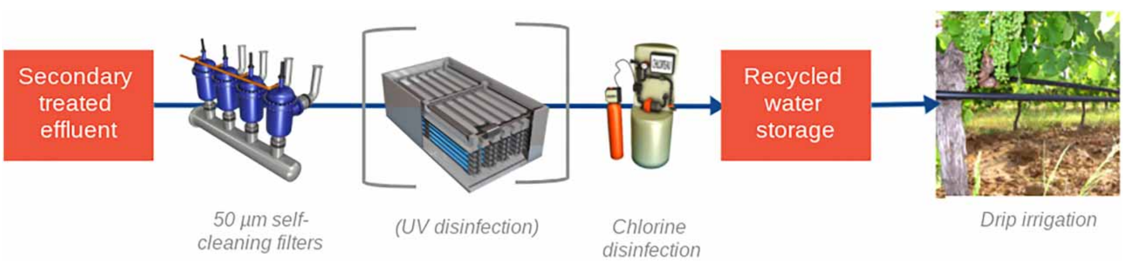
Water scarcity is a worldwide problem, which leads to unprecedented pressure on water supply in arid and semi-arid regions. Treated wastewater is an alternative water resource, therefore, its reuse for agricultural irrigation has been growing worldwide since the beginning of the 21st century. In several regions of wine-producing countries (e.g., Australia, California – USA, Spain), wastewater reuse appears to be the most accessible alternative, both financially and technically, for agricultural uses that notably do not require drinking water. From the summer of 2022, vine irrigation full-scale implementation will start with tertiary treated municipal wastewater in the French Languedoc region. This was made possible thanks to a collaborative research project conducted between 2013 and 2018 to address all potential health and environmental risks associated with this process. This research project was conducted in the south of France, with experimental and control plots both equipped with drip irrigation systems. All the results produced during the research project demonstrated the feasibility of applying this process for vine drip irrigation while effectively managing health and environmental risks and complying with the regulation. A social acceptance and economic study were also performed in order to broaden the scope of the project scalability evaluation.

Key words: drip irrigation, vineyard, water quality, water reuse

HIGHLIGHTS

- Low cost and robust technology.
- Process easy to 'Copy and adapt'.
- Consideration of environmental and health aspects.
- Sustaining the wine industry at a regional scale.
- First deployment at full-scale following the research project.

GRAPHICAL ABSTRACT



INTRODUCTION

Access to good quality water is one of the major human and economic challenges of this century. Population growth, and increasing and competing access to fresh water for industrial, agricultural, and potable purposes will not only severely reduce water availability per person but also create stress on biodiversity in the entire global ecosystem. As stated by the

Ministry in Charge of the Environment in early August 2022, over 100 French municipalities were short of potable tap water and relied on water deliveries by trucks. The European 2022 summer was assessed as the 'hottest on record' by the European Union (EU)'s environmental programme Copernicus, and was characterised by desiccating soils, particularly in Western regions (Copernicus 2022). In this context of increasing drought, the development of water reuse for agricultural irrigation is one of the relevant solutions for adapting to climate change; a solution which is still underestimated in France and in many countries around the world (Singh 2021). Treated wastewater in France is a largely untapped resource with less than 1% of this water being reused compared to some countries, such as Israel (90%), Spain (14%), or even Italy (8%) (WWAP 2017). Accounting for about 70% of freshwater extraction worldwide, agriculture is by far the largest water consumer. The ability to reuse resources (water and nutrients) from municipal wastewater effluents provides an opportunity to effectively tackle some of these challenges. Wastewater is the only water resource for which volume increases proportionally to urbanisation and economic development and consumption; it is therefore an interesting economic means to increase existing water supply.

In 2020, with 12.5 million hectolitres (Agreste 2021a) and 230,000 ha (Agreste 2021b), the Languedoc-Roussillon wine region represents 27% of France's production and 29% of its vineyards which ranks it among the top wine-producing regions of France; France being second in the world in terms of vine production (18%) and vineyard area (11%) according to the International Organisation of Vine and Wine (OIV 2021).

Nevertheless, a significant drop in yield has been observed over the past years primarily due to water stress and no irrigation system being available. Some of the vineyards are located near municipal wastewater treatment plants that are releasing treated water to the Mediterranean Sea. One of the solutions considered to maintain the area wine production yield is to use part of that secondary treated wastewater and polish it further through tertiary treatment for vine irrigation (Mendoza-Espinosa *et al.* 2019). Moreover, many studies around the world such as those of Laurenson *et al*. (2012), Acosta-Zamorano *et al.* (2013) and Kumar *et al.* (2015) and have shown the interest of this technique for the production and quality of the grape.

Between 2013 and 2016, Veolia led a collaborative research project in partnership with the INRAE research institute (LBE, Narbonne and UEPR, Gruissan), the Grand Narbonne public authority, AQUADOC and La Cave Coopérative de Gruissan, to assess the potential impacts of irrigating vine with tertiary treated municipal effluent, in comparison with surface water and potable water. Then, from 2016 to 2018, the project was continued in order to industrialise and ensure the reliability of the entire system before upscaling it at a larger scale for irrigating 80 ha of vine with treated municipal wastewater.

The project specific objectives were to remove existing barriers:

- Technical: reinforce competencies and know-how in terms of design and operation of the treatment scheme; demonstrate that health and environmental risks could be effectively managed.
- Social: support the acceptance of water reuse for vine irrigation by opening the project site to visitors and broadly communicating the results.
- Financial: assess the costs and benefits of the various irrigation scenarios.

METHODS

Water reuse for irrigation of crops or green spaces has been regulated in France since 2010, with an amendment in 2014 (Arrêté du 2 août 2010). This regulation defines four classes of water, from A to D, depending on the intended use and method of irrigation (sprinkler or drip).

Secondary treated effluent was used as source water for this study. This effluent was drawn from the municipal wastewater treatment plant of Narbonne Plage, a city in the Aude department of France, on the Mediterranean coast: 27,500 PE, conventional activated sludge without primary (Figure 1). A tertiary treatment pilot unit was built and installed to provide additional treatment and produce classes B and C water according to French regulation (Figure 2).

Two characteristic grapes of the region (Viognier and Carignan) were irrigated over three consecutive summers from 2013 to 2015 on testing parcels with the four different waters. Thanks to a dedicated irrigation network installed at the beginning of the project: treated wastewater classes B and C, surface water from Robine canal, and potable water (Figure 2).

This paper focuses on the use of class B treated wastewater in comparison with potable and surface water, but it does not present or discuss the results obtained for class C treated wastewater.

Extensive monitoring was conducted on:

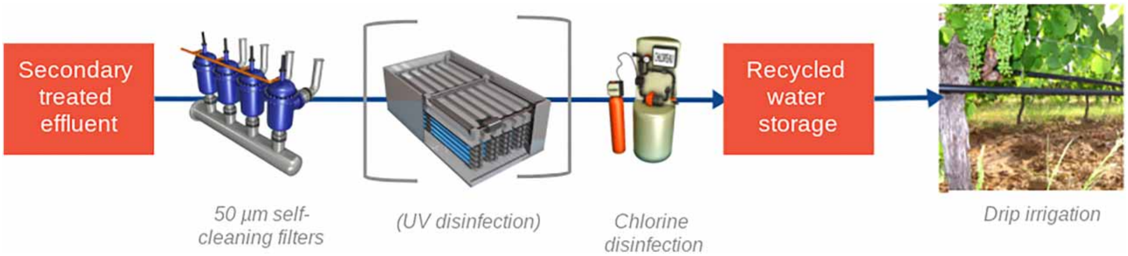


Figure 1 | Schematic diagram of the two tertiary treatment lines – UV disinfection for class B only.

Figure 2 | Aerial view of experimental site INRAE-UEPR. Vitis vinifera L cv. Viognier (left) and Carignan (right). red = surface water; yellow = treated wastewater class C; green = treated wastewater class B; blue = potable water. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wrd.2023.054.

- Water quality

During each season of irrigation, microbiological parameters were monitored by standard methods according to the French regulation: *Escherichia coli*, *Enterococcus*, RNA phages, and sulphate-reducing bacteria (SRB).

Samples points were as follows:

- WWTP inlet (raw municipal wastewater)
- Tertiary treatment pilot unit inlet (secondary effluent) and outlet (treated wastewater)
- Points of use: Viognier and Carignan

Before each irrigation season, the results obtained by standardised methods were communicated to the ARS (Agence Régionale de Santé, Ministry of Health) to validate the authorisation for vine irrigation.

For targeted microbial indicators, the Log-Removal Value (LRV, Equation (1)) achieved between the raw wastewater and reclaimed water.

$$\mathrm{LRV} = \mathrm{Log}_{10}\left(\frac{C_{\mathrm{in}}}{C_{\mathrm{out}}}\right) \tag{1}$$

where C_{in} is the concentration of target microbial indicator at the inlet of treatment and C_{out} is the concentration of target microbial indicator at the outlet of treatment.

Analytical monitoring of heavy metals was performed in parallel: cadmium, chromium, mercury, lead, and zinc.

- Groundwater

The piezometers located below the subplot surface water, treated water B and C, and potable water (see Figure 2) were monitored in duplicate: before any irrigation and then after each irrigation season. Each piezometer was dedicated to each type of irrigation water in order to assess the impact on groundwater quality. Only the aquifer from the Viognier plot was sampled as the Carignan aquifer was impossible to access in a practical way.

Monitoring of the same microbiological indicators as the ones followed in the three types of irrigation water was performed on the groundwater below the irrigated parcels: *E. coli*, *Enterococcus*, RNA phages, and SRB. Analytical monitoring of concentrations of mineral compounds: As, Bo, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Zn, P, Cl, NO_2, NO_3, PO_4, SO_4, NH_4, Na, K, Mg, Ca, and pH and conductivity was performed.

- Soil

For each subplot irrigated by one of the three waters (surface water, treated wastewater class B, and potable water), three samples were collected at a depth of 20 cm and mixed to constitute a representative soil sample. The same protocol was used for Viognier and Carignan plots.

Analytical monitoring of concentrations of mineral compounds (anions: sulphates, chlorides, nitrates, nitrites, phosphates; and cations: Pb, Cd, Fe, Mn, Ni, As, Cr, B, Zn, Ca, Cu, Na, K, Al, Mg, Ag) and conductivity was performed.

Physico-chemical parameters monitored in the different water types were used to assess the risk of infiltration problems in the soil. Thanks to SAR (Sodium Adsorption Ratio, Equation (2)) and EC_w (water salinity as expressed in electrical conductivity) as recommended by FAO (Etchebarne-Marjotte *et al.* 2016).

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (2)$$

where $[Na^+]$ indicates the concentration in sodium; $[Ca^{2+}]$ indicates the concentration in calcium; $[Mg^{2+}]$ indicates the concentration in magnesium.

- Plants, grape must, and wine

The quality of plant, must, and wine was also monitored for Viognier and Carignan plots during the three irrigation seasons (2013, 2014, and 2015). Wine was characterised using Total Acidity (TA) and Volatile Acidity (VA in g/l H_2SO_4), Alcohol By Volume (ABV), and Optic Density at 420 nm (OD_{420}).

The three types of water used for irrigation were considered: potable water, treated wastewater class B, and surface water.

In addition, the produced wine was analysed for 260 pesticide molecules and seven pharmaceutical compounds: carbamazepine, alpha-estradiol, beta-estradiol, oestrone, ethinyl oestradiol, bisphenol A, and ethyl carbamate.

RESULTS AND DISCUSSION

Research project

Water matrix

An in-depth microbiological analysis of the treated wastewater quality was undertaken. The results for *E. coli* concentrations, as well as LRV achieved for targeted microbial indicators between the raw wastewater and reclaimed water are shown in Table 1.

Specific attention was given to the elimination of SRB as the LRV varied from one campaign to another over the 3 years (from 1.4 to 3.6 log). In 2014, the average abatement was 2.6 log. Therefore, in 2014, tertiary treatment made it possible to achieve a level of quality B in 55% of cases, taking into account the measurement uncertainty linked to the analysis of this

Table 1 | Monitoring of the microbiological parameters in class B at the outlet of the pilot

	E. coli **n/100 mL** ***n*** **= 28**	**Enterococcus Log removal** ***n*** **= 24**	**SRB Log removal** ***n*** **= 28**	**RNA phage Log removal** ***n*** **= 28**
Target	<10,000	3	3	3
Mean	851	5	2.8 (in 2015)	3.4
Min	15	3	1.4	1.0 (in 2014)
Max	6.1	6	3.6	5.2

parameter. In 2015, the yield was slightly improved by changing the sieve size of the tertiary treatment. An average yield of 2.8 log was obtained. In general, in microbiology, this uncertainty is considered to be ± 0.5 log around the result. For SRB, the laboratory that carried out this analysis has control charts in its quality system for the analysis of SRB: these control charts allow measurement uncertainty to be assessed more precisely. For the SRB, this uncertainty at the 95% confidence level is ± 0.34 log around the result. By integrating this confidence interval, we can consider that level B reached 100% in 2015.

For RNA phage, the new sieve size during the second irrigation season led to an improvement of the LRV and an acceptable water quality level taking into account once again the confidence interval (mean = 3.4).

In parallel, *E. coli* and Enterococcus results have complied well beyond the regulations for each irrigation season.

In conclusion, class B water quality objectives are met for all the parameters after 3 years of optimisation of the process treatment.

The impact of storing and transporting treated wastewater was measured by comparing the quality of the water at the pilot outlet with that at the point of use. No degradation of the microbiological water quality was observed between the outlet of the pilot unit and the point of use (continuous operation – no storage, only hydraulic residence time in the irrigation network) (data are not shown).

The treatment process tested in 2015 (25 μm filtration + UV + chlorination) achieves the specifications of the B quality regulations for all microbiological parameters both at the pilot's outlet and at the point of use.

In addition to weekly microbiological monitoring, two measurement campaigns were carried out during each irrigation season on each type of water (surface water, potable water, and treated wastewater of quality B). Over the three irrigation seasons, heavy metals (cadmium, chromium, mercury, and lead) were not present in quality B irrigation water ($n = 2$). In surface water, copper, nickel, zinc but also lead were found ($n = 2$). In potable water, only copper was found ($n = 2$).

Groundwater matrix

All the microbial indicators monitored in the underground water below the irrigated parcels (*E. coli, Enterococcus*, RNA phages and SRB) were below the limit of quantification (LoQ), regardless of the type of water used for irrigation: surface water ($n = 3$), treated wastewater class B ($n = 3$), or potable water ($n = 3$).

When comparing the concentrations of these four microbial indicators in the groundwater before and after irrigation seasons in 2013 and 2014, no microbial contamination could be observed as a result of the irrigation with class B treated wastewater.

The physico-chemical results show that the ionic concentrations, as well as the pH and conductivity (measured at 25 °C) of the aquifer remain stable with no observable impact from the two irrigation campaigns (Table 2), showing that the source of the water used for irrigation has no influence on the ionic composition of the groundwater.

In conclusion, the monitoring carried out on the groundwater below the irrigated parcels did not reveal any microbiological or physico-chemical or physico-chemical degradation as a result of 2 successive years of irrigation, independently of the source of water tested, including class B reclaimed water.

Table 2 | Physico-chemical composition of the groundwater (LoQ: $N\_NH_4^+ = 0.0039$ mg/L; LoQ $N\_NO_2^- = 0.006$ mgN/L; LoN_$NO_3^- = 0.02$ mgN/L; LoQ $P\_PO_4^{3-} = 0.02$ $mgPO_4$/L)

Water origin	Sample	Cl (mg/L)	$N\text{-}NO_2^-$ (mg/L)	$N\text{-}NO_3^-$ (mg/L)	$P\text{-}PO_4^{3-}$ (mg/L)	SO_4^{2-} (mg/L)	Na (mg/L)	NH_4 (mg/L)	K (mg/L)	Mg (mg/L)	Ca (mg/L)	pH	Cond. (dS/m)
Potable	T0 – before irrigation	329	<LOQ	<LOQ	<LOQ	346	203	<LOQ	11	65	183	7.1	2.4
	2013 – after 1st season	331	<LOQ	<LOQ	<LOQ	371	244	<LOQ	13	74	218	7.2	2.5
	2014 – after 2nd season	368	<LOQ	<LOQ	<LOQ	257	210	<LOQ	14	55	178	7.2	2.1
Treated wastewater class B	T0 – before irrigation	258	<LOQ	<LOQ	<LOQ	246	149	<LOQ	12	43	163	7.1	1.9
	2013 – after 1st season	389	<LOQ	<LOQ	<LOQ	480	240	<LOQ	13	72	265	7.2	2.3
	2014 – after 2nd season	233	<LOQ	<LOQ	<LOQ	148	138	<LOQ	14	35	139	7.3	1.5
Surface water	T0 – before irrigation	218	<LOQ	<LOQ	<LOQ	278	132	<LOQ	16	51	167	7.2	1.8
	2013 – after 1st season	169	<LOQ	<LOQ	<LOQ	209	124	<LOQ	17	44	153	7.3	1.6
	2014 – after 2nd season	154	<LOQ	<LOQ	<LOQ	214	90	<LOQ	16	37	144	7.3	1.3

Soil matrix

As shown in Table 3 for the Viognier plot and Table 4 for Carignan, no significant impact occurs in the soils for all of the seven heavy metals, after three irrigation seasons, regardless of the water used.

In comparison with potable water and surface water, the treated wastewater has a higher salt concentration (Table 5). SAR and ECw (water salinity as expressed in electrical conductivity) from treated wastewater should be used to evaluate risks assessment. According to FAO recommendations on water quality for irrigation, a SAR between 3 and 6 and EC_w above 1.2 dS/m avoid any problem of infiltration in soil (Etchebarne-Marjotte *et al.* 2016).

For all the results, no significant change in the concentrations of the parameters measured emerges between the sampling campaigns carried out between 2013 and 2015 for both Viognier and Carignan. Therefore, irrigation with treated water leads to the absence of significant impact on soil quality.

Plant, grapes must, and wine

Variables characterising the quality of plant, must and wine were studied using principal component analysis (PCA). As most of the variance (82.9%) is explained by the first two principal components, the variables are plotted in two dimensions: the dimension with the most explained variance (55.8%) is called F1 and plotted on the horizontal axes, the second-most explanatory dimension (27.1%) is called F2 and placed on the vertical axis. Figure 3 illustrates the correlation circle obtained for the wine (adapted from Etchebarne-Marjotte *et al.* 2016) and shows a remarkable year effect, in terms of the level of maturity achieved from one year to the next, unrelated to the quality of irrigation water. The results are similar for plants and grapes (not shown): a year effect regardless of the type of water used for irrigation.

Moreover, an in-depth chemical analysis of wine was undertaken. Of the 260 pesticide molecules sought, we observed only the presence of three fungicides (spiroxamine, boscalide, and metalaxyl) at concentrations below the LOQ

Table 3 | Analytical monitoring of physico-chemical parameters on the soil matrix for Viognier – mean ($n = 5$)

Viognier plot	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Hg (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
T0 (control)	0.15	25.5	101.2	0.06	16.3	13.5	42.3
Potable water	0.16	18.0	109.2	0.04	13.5	12.0	34.8
Treated wastewater class B	0.16	20.7	120.0	0.04	15.0	12.8	38.8
Surface water	0.13	21.3	85.3	0.05	16.0	11.3	37.0

Table 4 | Analytical monitoring of physico-chemical parameters on the soil matrix for Carignan – mean ($n = 5$)

Carignan plot	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Hg (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
T0 (control)	0.22	32.0	76.5	<0.03	16.0	16.0	39.5
Potable water	0.25	27.5	82.5	0.05	16.8	14.5	37.2
Treated wastewater class B	0.25	31.8	86.3	0.06	14.8	16.2	37.0
Surface water	0.2	30.7	84.0	<0.03	16.0	13.3	34.3

Table 5 | Physico-chemical composition of the three types of water during 2013 ($n = 6$)–2014 ($n = 5$)–2015 ($n = 5$) seasons (mean values)

Water origin	$N\text{-}NH_4^+$ (mg/L)	$N\text{-}NO_2^-$ (mg/L)	$N\text{-}NO_3^-$ (mg/L)	$P\text{-}PO_4^{3-}$ (mg/L)	$S\text{-}SO_4^{2-}$ (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	pH	EC_w (dS/m)	SAR
Potable	<0.05	<0.03	2.4	<0.1	16.8	33.4	1.5	10.9	6.0	17.4	8.0	0.3	0.3
Treated wastewater class B	21.8	1.9	18.0	1.3	49.4	83.6	29.1	19.1	123.0	217.7	7.5	1.5	3.2
Surface water	<0.05	<0.03	1.15	0.1	47.5	65.8	2.5	9.4	15.9	21.9	8.2	0.4	0.5

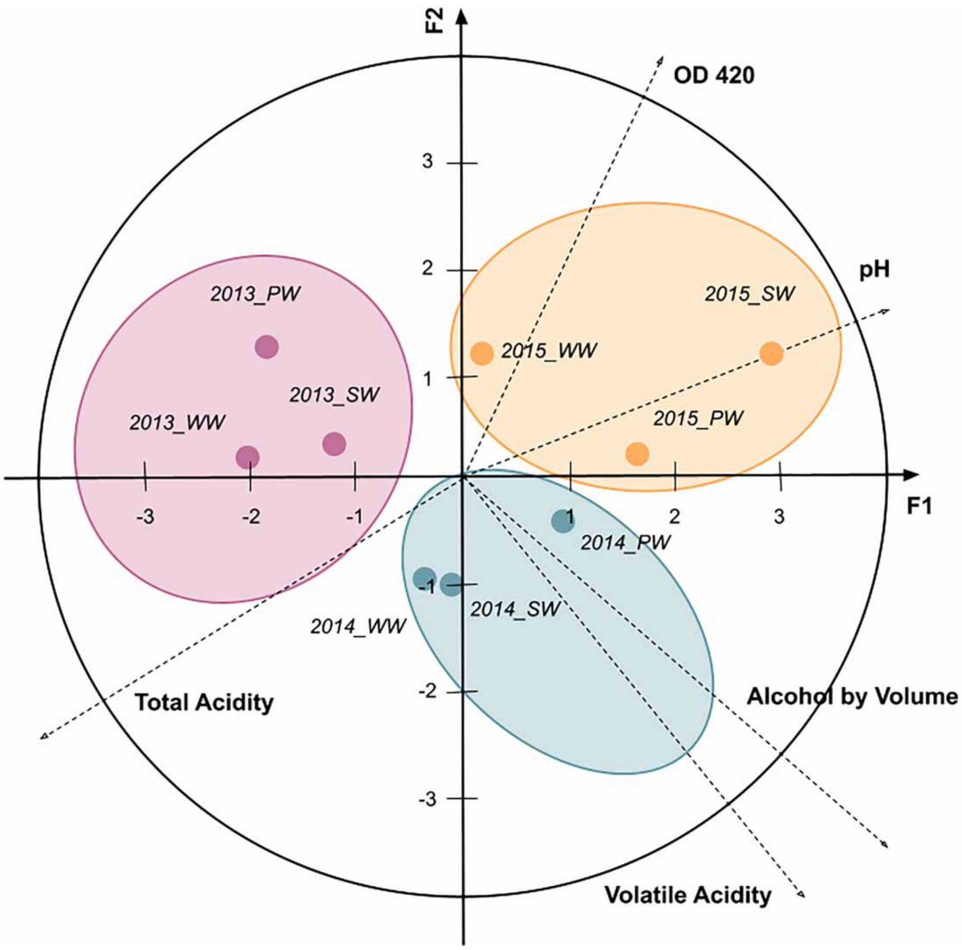


Figure 3 | Principal component analysis of physico-chemical composition of wine from the Viognier plot in 2013, 2014 and 2014 (PW, potable water, WW, treated wastewater class B, SW, surface water). Adapted from Etchebarne-Marjotte *et al.* 2016.

(LOQ = 0.01–0.05 mg/L) in the wine matrix ($n = 3$). The traces of fungicides found would come from the applications made in the vineyard, with regard to the traceability of the technical itinerary of the two plots.

Regarding the pharmaceutical compounds, the analytical report indicates that none of them (carbamazepine, alpha-estradiol, beta-estradiol, oestrone, ethinyl oestradiol, bisphenol A, and ethyl carbamate) was present in the wines resulting from the treated water irrigation – at the level of the current quantification limits on this type of matrix (respectively 10 μg/L for all the substances analysed except for ethyl carbamate which is at 50 μg/L).

Regarding the microbiological results, the eight wines produced (the same parameters as those analysed in the treated wastewater) are all negative in 2013, 2014, and 2015. The quantification thresholds are the same as those used on the water matrix, therefore, allowing the comparison of the data.

Finally, the results of the sensory evaluation of Viognier and Carignan wines show that the wine from the potable water is not statistically different from the wines irrigated by the tertiary treatment B. The wines produced do not show any tendency for qualitative differentiation between them, therefore no effect due to the sources of irrigation water.

All results produced during the research project demonstrated the feasibility of applying this process for vine irrigation while effectively managing health and environmental risks.

Full-scale implementation

Based on these positive results, it was decided to roll-out the water reuse solution to a larger scale irrigation scheme covering 80 ha of vine for commercial production. In order to do so, several barriers had to be addressed.

- Technical

In June 2020, the EU released a new regulation establishing minimum water quality standards for water reused across its member states (Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on minimum requirements for water reuse). This regulation that aims exclusively at crops irrigation is again articulated around four classes of water quality depending on the type of cultures and method of irrigation considered.

Irrigation of vine by drip irrigation has to comply with class C water quality according to the EU regulation, which is more stringent on maximum concentration of *E. coli* than the French regulation (i.e. $\leq$1,000/100 mL vs. $\leq$ 10,000/100 mL, respectively, EU class C and French class B waters), but has no additional requirement for the removal of other microbial indicators (such as coliphages for pathogenic viruses, or spore-forming sulphate-reducing bacteria for protozoa). The EU regulation does ask for a water reuse risk management plan to be implemented.

While the results obtained during the research project demonstrated that it was not particularly challenging to meet the EU class B or C limit, the tertiary treatment process was upgraded by replacing the 50 μm self-cleaning filters by a more robust automatic backwashing glass marbles pressurised filter. The complete tertiary treatment process developed as a standard solution for water reuse by Veolia has a capacity of 50 m^3/h and all equipment fits within a 20 ft. container called the REUT box (see Figure 4).

This reuse box as well as upstream/downstream flexible soft storage tanks and associated piping has been installed at the back end of the municipal wastewater treatment plant and was ready for its first season of irrigation during summer 2021.

In addition to the tertiary treatment unit, a 7.8 km network had to be installed along with 13 connected irrigation meters and valves to irrigate the 80 ha of vine.

- Administrative

In order to fully manage the risks associated with this water reuse scheme from production to use, an association of irrigators had to be created. This association is responsible for the distribution of the treated wastewater from the treated water storage tanks to the limit of the irrigated parcels and the irrigation valves that are controlled by winegrowers. It then becomes their responsibility to use this water for drip irrigation on their parcels (Figure 5).

A request for irrigation with reclaimed water had to be filed and has been approved by the competent authority (the Prefecture that is supported by the local health agency).

- Financial

The investment cost was heavily subsidised by local and European funds as described in Table 6.

The cost to the winegrowers is ultimately 0.65 €/m^3 of water used for irrigation. This includes 0.38 €/m^3 for the operations and maintenance costs of the tertiary treatment plant (manpower, maintenance, consumables, analytical) as well as 0.27 €/m^3 for the irrigators' association (amortisation of 20% of the investment costs and maintenance). This is shown in Figure 6.

The impact targeted for the winegrowers is a security on yield resulting in a net increase of income of 350 €/ha.

Figure 4 | Pictures of a standard containerised 10 m^3/h REUT box.

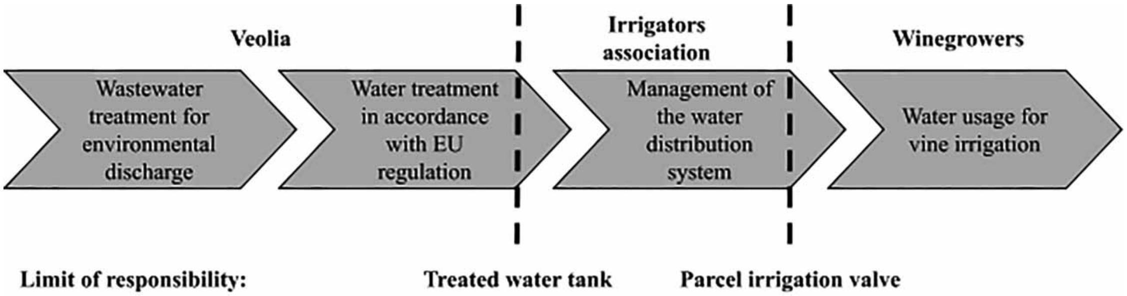


Figure 5 | Chain of responsibility for the scheme operators.

Table 6 | Breakdown of investment costs and subsidies

	Investment costs (k€)	Subsidies (%)	Funding body	Remaining costs (k€)
Tertiary treatment	532	100	Occitanie Région Narbonne City	0
Distribution system	774	80	FEDER European Fund Occitanie Region Aude Departmental Council	155

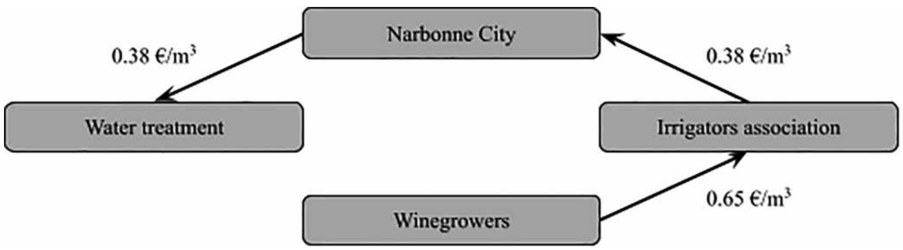


Figure 6 | Breakdown of the O&M costs.

CONCLUSIONS

All the results produced during the research project showed that the produced treated water reached the physico-chemical and microbiological quality complying with the regulation. No degradation occurred in the primary irrigation network: from the outlet of tertiary treatment to the connection serving each irrigated plot.

This demonstrated the feasibility of applying this process for vine drip irrigation while effectively managing health (plant, grapes, must, and wine) and environmental risks (soil and groundwater). In this vineyard, located nearby a municipal wastewater treatment plant, there is a willingness to pay for water by winegrower. Wastewater reuse is, therefore, the only way to feed an irrigation system to cope with the significant drop in yield.

To roll-out the water reuse solution to the industrial scale, it was important to take into account social acceptability. For local residents and consumers, health and environmental safety is at least as important as technical performance.

Hence, water reuse is appropriate for vine drip irrigation in this top wine-producing region of France and is a relevant solution for winegrowers to cope with increasing water stress.

ACKNOWLEDGEMENTS

Occitanie Region, BPI France, Agence de l'Eau Rhône-Méditerranée et Corse and le Grand Narbonne are acknowledged for their financial support as well as the project partners: INRAE, Aquadoc, Cave Coopérative de Gruissan, and Grand Narbonne.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 18 July 2022; accepted in revised form 30 June 2023. Available online 19 July 2023