Ciência Téc. Vitiv. 35(1) 1-15. 2020

WATER AND WASTEWATER MANAGEMENT FOR SUSTAINABLE VITICULTURE AND OENOLOGY IN SOUTH PORTUGAL – A REVIEW

GESTÃO DA ÁGUA E DAS ÁGUAS RESIDUAIS PARA UMA VITICULTURA E ENOLOGIA SUSTENTÁVEIS NO SUL DE PORTUGAL – REVISÃO

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(Received 13.09.2019. Accepted 31.01.2020)

SUMMARY

Assessing sustainability of the wine industry requires improved characterization of its environmental impacts, namely in terms of water use. Therefore, quantification of water inputs and wastewater (WW) outputs is needed to highlight inefficiencies in wine production and related consequences for the environment. Water use and WW generation in irrigated viticulture and oenology remains insufficiently quantified for dry Mediterranean regions (*e.g.* South Portugal). This paper is focused on wine production under warm and dry climate conditions in the winegrowing region of Alentejo (South Portugal). This region experiences increasingly dry conditions, while the irrigated area keeps expanding, which puts exacerbates the pressure on existing local and regional water resources. Additionally, more erratic variation in climate conditions and the tendency for increasingly extreme climate events (*e.g.* heat waves) pose more challenges to Alentejo's wine sector. We conclude that quantitative information on water use and management is not always easy to obtain or access, which hinders improved strategies and/or policies for water use at farm, winery and region-level. Up-to-date statistics and robust metrics can help to better characterize water use and WW flows for Alentejo's wine region, while optimizing management in vineyards and wineries, in companies and region-wide. The paper is focused on a "Farm-Winery" scenario, which is the most common in South Portugal's wine sector.

RESUMO

A avaliação da sustentabilidade da indústria vitivinícola requer uma caracterização detalhada do seu impacto ambiental, nomeadamente ao nível do factor água. A quantificação detalhada dos consumos de água e das águas residuais produzidas (WW) é crucial para identificação de ineficiências na indústria da vinha e do vinho. A utilização da água e a gestão dos efluentes em viticultura regada e na adega permanecem pouco quantificados nas regiões mediterrânicas. O presente trabalho centra-se na produção de vinho em condições de clima quente e seco, tomando como exemplo a região vitivinícola do Alentejo (Sul de Portugal). A região está sujeita a situações de seca mais frequentes e severas, enquanto a área regada continua em expansão, o que pressiona os recursos hídricos locais e regionais. Além disso, as condições climáticas altamente variáveis e a maior tendência para eventos climáticos extremos (*e.g.* ondas de calor) colocam desafios ao setor vitivinícola no Sul de Portugal. Concluímos que a informação quantitativa relativa ao uso e gestão de água não está sempre facilmente disponível, limitando a otimização de estratégias e/ou políticas para o uso da água ao nível da vinha, da adega e da região. Dados atualizados e indicadores robustos podem ajudar a caracterizar melhor o uso de água e a geração de água residual na região vitivinícola do Alentejo, otimizando a gestão na vinha e na adega, ao nível da empresa e da região. O artigo centra-se num cenário de produtor-engarrafador ("Farm-Winery"), que é o mais comum no setor vitivinícola no Sul de Portugal.

Key words: Irrigated viticulture, sustainable water use, water metrics, water scarcity, wastewater reuse.
Palavras-chave: Escassez de água, métricas de água, reutilização de águas residuais, uso sustentável da água, viticultura regada.

INTRODUCTION

Water use in viticulture and oenology demands improved quantification to support present and future adaptation strategies of the wine industry to climate change, while increasing water use efficiency and minimizing environmental burdens (Chiusano *et al.*, 2015; Costa *et al.*, 2016; Martins *et al.*, 2018). The challenges posed to the wine industry extend to wastewater (WW) generation and management in

Article available at https://www.ctv-jve-journal.org or https://doi.org/10.1051/ctv/20203501001

both viticulture and oenology phases (Castex *et al.*, 2015; Peth *et al.*, 2017). This is particularly important for Mediterranean regions, characterized by hot dry summers and mild winters, and increasingly exposed to extreme climate events (Fraga *et al.*, 2018; Lopes *et al.*, 2018).

Portugal is a typical Mediterranean wine producer, with around 191,000 ha of vineyards and a wine production of about 6.5 MhL in 2017 (IVV, 2018). It is the 11th largest producer worldwide and the 9th largest amongst global wine exporters (OIV, 2018).

The wine-producing region of Alentejo (South Portugal) is one of 14 Portuguese wine regions. It has a total vineyard area of 23,879 ha and accounts for approximately 12.5% of the country's total wine grape production area (IVV, 2018). Most of the Alentejo region has a Csa climate, according to the Köppen-Geiger updated classification (Peel *et al.*, 2007), characterized by warm and dry summers (IPMA, 2017). Precipitation is very low or absent in summer and air vapour pressure deficit (VPD_{air}) can be extremely high (up to 8 kPa), generating high crop evapotranspiration losses (COTR-ATEVA, 2009; Barroso *et al.*, 2017). Bioclimatic indices such as the Dryness Index (DI) (Riou *et al.*, 1994), which help to assess regional suitability for wine production and predict climatic impact on viticulture, show a tendency for increasingly severe drought conditions in Alentejo (Figure 1) (Fraga *et al.*, 2018; Lopes *et al.*, 2018). This is in line with the fact that the region is experiencing more frequent heat waves, which poses increasing risks to the sector (Lopes *et al.*, 2018; Silvestre *et al.*, 2018). In this context, irrigation emerged as a major tool to overcome the constraints posed by adverse climate conditions and support risk management, *e.g.* due to heat waves (Silvestre *et al.*, 2018). Consequently, the total irrigated vineyard area in Alentejo is nowadays largely above 10,000 ha (more than 50% of total surface) (Costa *et al.*, 2019). This was a fast increment, if we consider that in 2002 there were only 4,600 ha with irrigated vineyards (CVRA, 2002), and the trend should remain, supported by the Alqueva dam (EDIA, 2018).

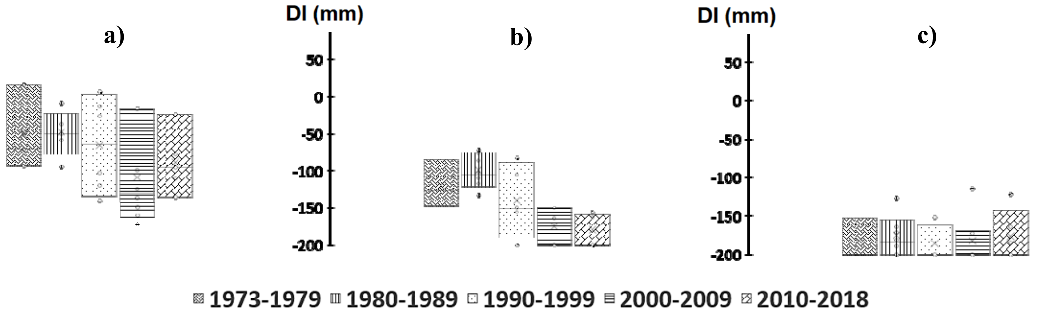

Figure 1. Ten-years interval variability of the Dryness Index (DI, mm) (Riou *et al.*, 1994), for **(a)** Portalegre, **(b)** Évora and **(c)** Beja (Alentejo region, South Portugal) using datasets from local weather stations. DI = Wo + P - Tv - Es, where Wo is the soil water reserve at April 1 (assumed as 200 mm); P is the accumulated precipitation (mm); Tv is the vineyard's potential transpiration (mm); Es is the soil water loss by evaporation (mm). The DI estimates soil water availability taking into account vine's transpiration, soil evaporation and precipitation between April 1 and September 30 (in the Northern Hemisphere). The box-plots are bounded on top by the 3rd quartile (Q3), on the bottom by the 1st quartile (Q1) and divided by the median (Q2). The average value of the series is represented by (x) and (o) indicates the DI values. The top whisker is defined as Q3+1.5xIQR and the lower whisker as Q1–1.5xIQR, where IQR=Q3-Q1.

Variabilidade observada para um período de dez anos do Índice de Secura (DI) (Riou *et al.,* 1994), para a região de (a) Portalegre, (b) Évora e (c) Beja (região do Alentejo, Sul de Portugal). DI = Wo + P - Tv - Es, onde Wo é a reserva de água do solo a 1 de Abril (assumido como 200 mm); P é a precipitação acumulada (mm); Tv é a transpiração potencial da vinha (mm); Es é a perda de água no solo por evaporação (mm). O DI estima a disponibilidade hídrica do solo considerando a transpiração da videira, evaporação do solo e precipitação ocorridas entre 1 de abril e 30 de setembro (no Hemisfério Norte). A caixa de bigodes é delimitada no seu topo superior pelo terceiro quartil (Q3), na parte inferior pelo primeiro quartil (Q1) e dividida pelo valor da mediana (Q2). O valor médio da série é representado por (x) e (o) indica os diferentes valores de DI. A barreira superior é definida como Q3+1.5xIQR e a barreira inferior é definida como Q1-1.5xIQR, onde IQR=Q3-Q1.

Water accounting in irrigated agriculture is often characterized by poor metrics and scarce data reporting (Corbo *et al.*, 2014; Santiago-Brown *et al.*, 2015; Liu *et al.*, 2017; Pfister *et al.*, 2017; EU Commission, 2017). In addition, indicators to assess the sustainability of the wine industry vary between regions and countries, making it difficult to compare "companies/farms" performance (Santini *et al.*, 2013;

Corbo *et al.*, 2014; Oliveira *et al.*, 2019). In Portugal, recent efforts in the wine sector to improve its environmental sustainability are reported in several studies (Neto *et al.*, 2013; Quinteiro *et al.*, 2014; Engel *et al.*, 2015; CVRA, 2016), but information remains scarce. In addition, auditing for environmental performance demands more precise water use monitoring in farms and wineries, as well as data on wastewater production and/or quality (EPA, 2004). In parallel, more homogeneous standards/metrics for sustainability, independently of the *terroir* are on demand (Costa *et al.*, 2016; Oliveira *et al.*, 2019).

Therefore, the major aims of this review are to point out the risks of increasingly dry conditions for irrigated viticulture and oenology in South Portugal, while emphasizing the role(s) of improved water metrics for more efficient water use and WW management in the vineyard and in the winery.

WATER USE AND WASTEWATER PRODUCTION IN VINEYARDS AND WINERIES

A strategic approach towards more sustainable water use in dry regions' wine production must involve the combined assessment of water needs and WW production/management in both vineyards and wineries. This is highly relevant for Mediterranean regions, *e.g.* South Portugal, where values of 88 to 264 L of water can be spent per litter of wine produced (Engel *et al.*, 2015). More recent literature points to even higher values of annual water footprint, reaching 360 L per 0.75 L bottle (450 L per litter of wine), as referred by Saraiva *et al.* (2019) for South Portugal wines. The Portuguese wine industry is based on small to medium size vineyards and small wineries, with 98% of them having production volumes below 2000 hL (IVV, 2016). Therefore, a "Farm-Winery" approach, in which vineyards and wineries are considered in a single stream grape system, will represent the majority of Portuguese viticulture and oenology stakeholders and can be used to support the analysis of water use and management in the Portuguese vine and wine sector (Oliveira *et al.*, 2019).

Water use and wastewater production issues in the vineyard

In dry areas, viticulture accounts for the highest fraction of water used in wine production, reaching values comprised between 70 to almost 90% of total water use in some cases (Ene *et al.*, 2013; Correia, 2015; Saraiva *et al.*, 2019). Despite grapevine being considered well-adapted to dry conditions, irrigated cultivation uses a considerable water volume per season under Mediterranean conditions (EDIA, 2018; Table I).

Water use in the vineyard depends on several factors: 1) Plant – canopy leaf area and canopy gas exchanges, stem and root morphology, plant hydraulics, phenology, genotype; 2) Soil – depth, texture, organic matter content, water availability, soil temperature (T_s); 3) Atmospheric conditions – rainfall (R), air vapor pressure deficit (VPD_{air}), air temperature (T_{air}), wind speed (W_s); 4) Agronomic choices and practices – soil preparation, plant density, rootstock/variety combination, row orientation, floor management, training system, canopy management (Figure 2).

In the Alentejo wine region, irrigation needs are expected to vary between 2,500-3,000 m^3/ha per year for an average production of 7.5 to 10 t/ha (EDIA, 2018). Nevertheless, these indicative values are 30-50% higher than the ones observed under deficit irrigation, which is already being implemented in commercial vineyards in the region for some years (see Table I).

More sustainable grapevine irrigation should supply enough water, at the right moment, to guarantee a profitable yield and winemakers' desired berry composition without compromising vine longevity. Deficit irrigation strategies should be based on a precise monitoring of atmospheric conditions, soil water content and plant water status. In addition, Alentejo has a wide annual climate variability (see Figure 1 and Table I), with increasingly drier winters and warmer temperatures in recent years, which pose additional risks to the wine sector in the region. Even though the degree of corporatization has been increasing in the region, and with it the adoption of better management strategies (INE, 2013; 2016), there is still a large variation among farms regarding irrigation efficiency, with timing and volume of irrigation being decided mostly through experience and observation, instead of atmosphere/crop/soil monitoring and precise water metrics (COTR-ATEVA, 2009; Levidow *et al.*, 2014). Audits to water use in farms and wineries are also not a widely adopted practice (Radke *et al.*, 2015). This suggests that a wider network of simple monitoring sensors, more technical support and broader implementation of sustainability programs for the sector, will be a step forward to optimize water management at company and region level.

Table I

Climate conditions and irrigation water volumes applied under sustained deficit irrigation (SDI) conditions implemented in a field trial at a commercial vineyard in the Alentejo winegrowing region (Reguengos) along three consecutive years (Costa *et al.*, 2019). Average rainfall (mm); Reference Evapotranspiration (ET_o); T_{air} – air temperature; Irrigation volume: water volume applied during the irrigation period; SDI management was based on vine leaf water potential threshold of ~0.4 to 0.5 MPa

Clima e volumes de água de rega aplicados ao longo de três anos consecutivos em condições de rega deficitária sustentada (SDI) implementada num ensaio conduzido numa vinha comercial da região do Alentejo (Reguengos) (Costa et al., 2019). Precipitação média (mm); Evapotranspiração de referência (ET_o); T_{air} – temperatura do ar; Volumes de rega: dotação aplicada durante o período de rega. A gestão da rega deficitária foi baseada em limiares na medição do potencial hídrico foliar de base (limiares entre ~0.4 a).) 0.5 MPa.

Year	**Mean/ Max T_{air} (Jun - Aug) (ºC)**	**Rainfall during dormancy period (Oct - Feb) (mm)**	**Rainfall during growth period (Mar - Aug) (mm)**	**Cumulative ET_o (Mar - Aug) (mm)**	**SDI irrigation volume (May/Jun - Aug) (mm)**
2013	**24.5/34.3**	**308**	**255**	**820**	**111**
2014	**23.2/32.8**	**321**	**157**	**776**	**67**
2015	**24.9/34.6**	**288**	**95**	**940**	**165**

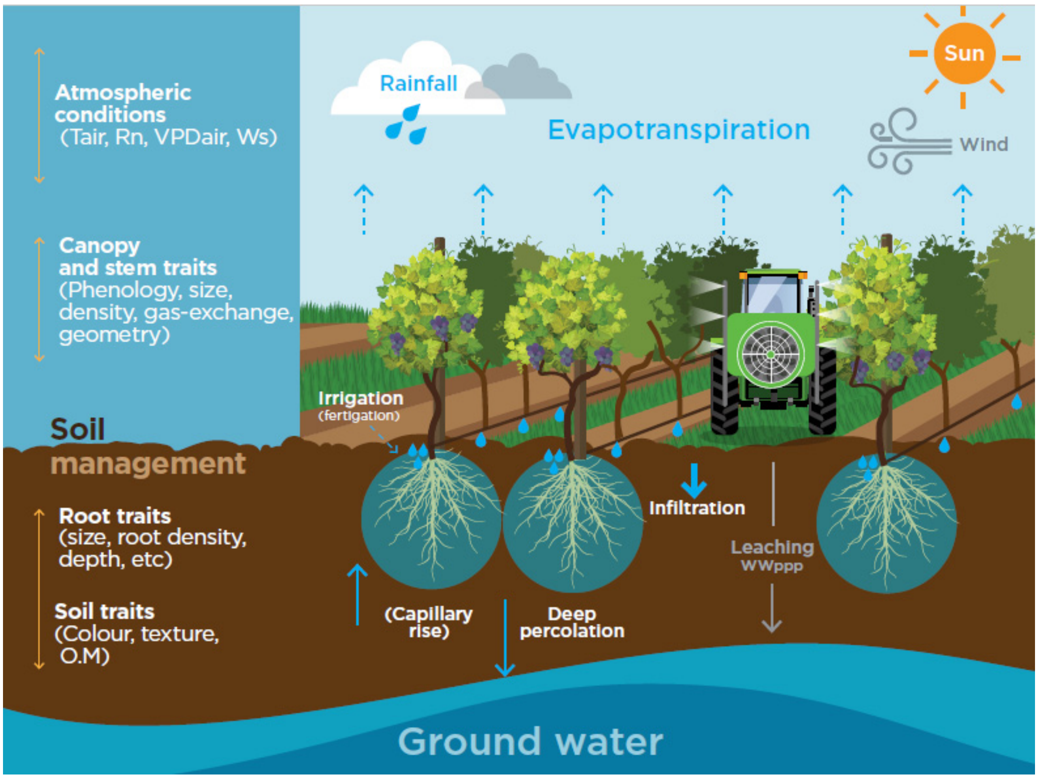

Figure 2. Illustrative diagram showing the main soil-plant-atmosphere water fluxes taking place in an irrigated vineyard with cover crops in the interrow and including the WW fluxes related to the spraying of plant protection products (PPP) – WW_{PPP}. Irrigation can also include fertigation. Evapotranspiration accounts for soil, grass and vines. T_{air} – Air temperature; VPD_{air} – Air vapour pressure deficit; W_s – Wind speed; R_n – Solar Radiation; O.M. – Organic matter;.

Diagrama ilustrando os principais fluxos de água numa vinha regada com enrelvamento na entrelinha, incluindo os fluxos de águas residuais (WW) relacionados com a utilização de pesticidas (“PPP”) – WW_{PPP}. A rega também pode permitir fertilização. Evapotranspiração inclui a componente solo, relvado e videiras. T_{air} – Temperatura do ar; VPD_{air} – Deficit de pressão do vapor do ar; W_s – Velocidade do vento; R_n – Radiação solar; O.M. – Matéria Orgânica.

A much less described item in conventional viticulture is the volume of WW generated in the vineyard ($WW_{vineyard}$), mainly related to spraying of plant protection products (PPP) and/or improper disposal/management of PPP residues (Doruchowski *et al.*, 2014; Otto *et al.*, 2015). The $WW_{vineyard}$ may represent a minor percentage of the overall volume of water used in irrigated vineyards, but its impact on soil and groundwater contamination can be significant. For example, Rochard and Codis (2004) indicate that for a volume of 108 to 1400 L of water used per spraying treatment, a total amount of 41 L and 354 L of WW can be generated, respectively. In turn, the volume of clean water used to wash sprayers has been shown to vary between 95 L and 190 L per day of spraying application (IFV, 2010). Such range of variation can be due to technical and operational factors, such as spraying frequency, sprayers' dimension, operators' experience, or cleaning equipment specificities (*e.g.* high pressure cleaning saves about 50% of water relatively to conventional sprayers), but also to the characteristics of the *terroir* (IFV, 2010). The WW volumes derived from washing protective clothing and empty pesticide containers should be accounted as well, but data is often unavailable.

The wine industry is strongly committed to reduce the amount of PPP in viticulture (EIP-AGRI, 2019), namely by adoption of Integrated Crop Management (ICM) and biological control measures and/or novel dosing methods based on dynamic variation of canopy leaf area, phenology and climate conditions (*e.g.* based on modelling software and decision support systems) (Kuflik *et al.*, 2009; Gil *et al.*, 2011, 2014; Pérez-Expósito *et al.*, 2017). For example, it is now possible to optimize the applied volume of PPP as function of canopy area/volume, resulting in a more precise site-specific application, with considerable water savings (Gil *et al.*, 2014; Campos *et al.*, 2019). Nevertheless, this occurs mostly in large-scale operations and companies.

Water use and wastewater production issues in the winery

Water use in the winery is mainly related to cleaning operations – equipment, tanks, vats, barrels, presses, de-stemmers, reception hoods, as well as taps, floors, walls and pipes (Pirra and Bianchi, 2007; Andreattola *et al.*, 2009; Oliveira *et al.*, 2019). Water consumption depends on type and size of the winery, the type of wine produced and the adopted winemaking technology (Andreattola *et al.*, 2009; GWRDC, 2011).

The maximum water consumption in the winery occurs during vintage and in the 1st racking period (Duarte *et al.*, 2004; Oliveira and Duarte, 2016; Oliveira *et al.*, 2019). The WW flows are proportional to the vintage duration (GWRDC, 2011). Duarte *et al.* (2004) and Oliveira and Duarte (2016) proposed a simpler approach in which two or more activities are combined. They consider two periods: vintage and 1st racking (Period I) – characterized by high peak flows and high pollution loads – and the remaining activities *e.g.* bottling, are encompassed in Period II – characterized by reduced water flows and medium/low pollution loads. The lack of distinction between these two periods may explain the large variation reported in literature for the volumes of water used in wineries (L water/L wine produced) (Table II).

TABLE II

Water consumption/wastewater production in the winery during the winemaking process based on previous literature.

Consumo de água / produção de águas residuais na adega durante o processo de vinificação, baseados em literatura existente.

Volume water (L) / wine produced (L)	Source
< 1	Andreattola *et al.* (2009); Rochard and Kerner (2009); Welz *et al.* (2016).
1-4	Shepherd *et al.* (2001); Duarte *et al.* (2004); Vlyssides *et al.* (2005); Fernández *et al.* (2007); Stephano *et al.* (2008); Andreattola *et al.* (2009); Bolzonella *et al.* (2010); Lucas *et al.* (2010); Amienyo *et al.* (2014); CSWA (2014); Radke *et al.* (2015); Roman-Sanchez *et al.* (2015); Oliveira and Duarte (2016); Da Ros *et al.* (2016); Oliveira *et al.*, (2019); Esporão (2018).
4-8	Kumar and Kookana (2006); Andreattola *et al.* (2009); Mosse *et al.* (2011).
>8	Van Schoor (2005); Kumar and Christen (2009); Andreattola *et al.* (2009).

Similarly to vineyards, WW production in wineries remains not fully characterized. Data collected in Alentejo shows that 60-86% of the total WW is produced in Period I (Oliveira and Duarte, 2015), which is similar to Italian wineries, where 78% of the WW is generated during vintage and 1st racking (Lofrano *et al.*, 2009). Likewise, WW characteristics need a better assessment, as they depend on the working period and the type of winemaking technologies used.

The winery WW contains grape pulp, skins and seeds (Devesa-Rey *et al.*, 2011; Oliveira and Duarte, 2016). This complex matrix of different flows comprises suspended solids, readily biodegradable compounds (fructose, glucose and ethanol) and other difficult-toremove compounds (*e.g.* surfactants and polyphenols), which may be problematic when directly discharged in treatment system facilities (Oliveira *et al.*, 2009; Mosse *et al.*, 2011; Okada *et al.*, 2013). The organic matter present in WW generally ranges from 1 to 25 g of COD L^{-1} and depends on the working period (Petruccioli *et al.*, 2002; Lofrano *et al.*, 2009). Higher organic loads are normally originated in Period I, but high levels of COD can also be recorded in Period II (50 g COD L^{-1}) probably due to inadequate lees removal (Oliveira *et al.*, 2009). In the same way, the biodegradability ratio (BOD_5/COD) of WW depends on the working periods, being higher for the WW generated in Period I (Fernández *et al.*, 2007; Oliveira *et al.*, 2009).

Keeping the complete record of WW flow streams helps winery managers to estimate the required storage and treatment infrastructures, because it depends on the size of the winery, the grape variety and/or the harvest period (Oliveira *et al.*, 2009; Mosse *et al.*, 2011; Welz *et al.*, 2016). Other critical issues for efficient WW management in the wineries are the wide range of pH values in WW, as well as the high dissolved solids content and the presence of indigenous microorganisms, *e.g.* bacteria and yeast (Eusébio *et al.*, 2005; Mosse *et al.*, 2011).

WATER METRICS AND ENVIRONMENTAL IMPACT ASSESSMENT IN WINE PRODUCTION

Water use indicators for the vineyard and the winery

Water metrics in wine production must rely on robust indicators and methods that assist growers and wine managers in understanding water cycle streams in their farms and wineries, respectively (Christ and Burrit, 2013; Peth *et al.*, 2017). Medrano *et al.* (2015) consider different indicators to evaluate water use efficiency, ranging from leaf eco-physiological level (*e.g.* Net photosynthesis/Transpiration = Instantaneous Water Use Efficiency) to crop level (Yield/Water use = Crop water use efficiency). In a more practical approach, Skewes (1998) proposed several basic indicators to evaluate water productivity in the vineyard. Skewes (1998) includes the ratio between grape yield and the volume of irrigation water used (t/m^3), but also considers the ratio between profit and the volume of water used (profit (€)/water volume (m^3)). In addition, and to incorporate the potential environmental impact of the $WW_{vineyard}$, we may consider as well the volume of WW derived from PPP application (WW_{PPP}), which would be translated into another potential indicator of water usage/productivity: volume of WW_{PPP} produced per kg of harvested grapes. However, this indicator can have a large variation, due to the inter-annual variability of weather conditions (see Table I) and related pest pressure, as it occurs under Mediterranean conditions.

In the winery, the volume of WW generated per litter of wine produced (WW_{winery}) is a widely adopted metric (Table II). However, calculation of a global indicator for small and small to medium farm-wineries must take into account the type of grape that is processed (*e.g.* white *vs*. red), the labour periods (Periods I and II) and the implementation of best available technics (BAT) (see Table III). This allows stakeholders to evaluate WW_{winery} output along different labour periods, for different grape types, production specificities (*e.g.* kg grapes production/year), vinification rate and annual water consumption in oenological processes, assuming that all water consumed is discharged as wastewater. This approach would support decision making on winery technologies to reach treated wastewater quality requirements.

Water use indicators: limitations and possible applications to Alentejo wine production

The environmental impact of water use by agriculture is usually amplified in dry climates. Wine production in dry areas (*e.g.* Alentejo - Portugal) can promote water abstraction and/or pollution of surface and/or groundwater due to WW_{PPP} runoff in the field and/or by WW_{winery} mismanagement. Therefore, a set of indicators is needed to support the assessment of environmental impacts of the wine industry, with focus on water and wastewater management. Indicators focused on water stress/water scarcity can support water use monitoring and management at regional and local levels, contributing to assess the impact of agriculture on water availability, consumption and pollution (OECD, 2011; EU Commission, 2012; Moore *et al.*, 2015; Liu *et al.*, 2017; Xu and Wu, 2017). Among these indicators we can consider the Relative Water Stress Index (RWI) (Vörösmarty *et al.*, 2000), also defined as the Water Availability Index (WAI) (EU Commission, 2012), which provides a measure of water demand pressures from domestic, industrial and agriculture sectors in relation to local and upstream water supplies. In turn, the Water Stress Index (WSI; Pfister *et al.* 2009), is a variation of the RWI that incorporates climate variability, which can be relevant for regions such as Alentejo, characterized by a wide inter-annual climate variation (see Figure 1 and Table I).

TABLE III

Global and dedicated indicators for wastewater flows in the winery (WW_{winery}) (Adapted from Duarte *et al.*, 2004; Oliveira e Duarte, 2016 and Oliveira *et al.*, 2019)

Indicadores globais e dedicados para fluxos de água residual tratada em adega (Adaptado de Duarte et al., 2004; Oliveira e Duarte, 2016 e Oliveira et al., 2019).

Indicators			**Winery type** **Small / Medium**	
Global		Type of grape	White	Red
		L_{water}/L_{wine}	1-2	2-3
With BAT *			0.6-0.7	
Dedicated	**Period I (30-60 days)**	Wastewater ratio (Period I/year)	0.7	
	Period II (305-335 days)	Wastewater ratio (Period II/year)	0.3	

* BAT implementation leads to 30-40% reduction in water consumption (data not shown).

The use of regional and global indicators could be optimized if combined with other methodologies such as Water Footprint (WFP), or Life Cycle Assessment (LCA), for a more robust analysis of the environmental impact of agricultural production (Brown *et al.*, 2011; Liu *et al.*, 2017). Indeed, the WFP accounts for both direct and indirect use of water by a consumer or producer and it works as a spatial-temporal indicator of freshwater use in agro-food products, including wine (Hoekstra *et al.*, 2011; Ene *et al.*, 2013; Lamastra *et al.*, 2014; Bonamente *et al.*, 2015; Saraiva *et al.*, 2019). However, WFP methodology is not consensual (Perry, 2014) and inconsistencies in underlying used water databases pose concern among researchers (Vanham and Bidoglio, 2013). Nevertheless, Bonamente *et al.* (2015) showed that red wine production in Umbria (Italy) had a WFP of 632 L/bottle (0.75 L), which agrees with the global WFP value proposed by Hoekstra *et al.* (2011). In turn, values presented by Capri (2016) for Italian certified wines ("VIVA Sustainable Wine") were shown to vary between 530 L/bottle (0.75L), for the Lambrusco variety, up to 1230 L for Sagrantino Montefalco. The major contribution (98.3%) for the WFP relates to green water (rainfall), with a minor contribution of grey water (polluted water) (1.2%) and blue water (0.5%). Ene *et al.* (2013) described another pattern of WFP for low-yield Romanian vineyards (less than 4 t/ha) of the Iasi County and using multiple varieties (*e.g.* Fateasca alba, Sauvignon, Chardonnay, Riesling). Although the major component is still green water, the distribution of the WFP components was in this case 82% for green water, 15% for grey water and 3% for blue water. Moreover, as WFP values for food products vary with geographic location and climate, these factors must be considered when analysing the wine sector and related wine WFP. Indeed, inter and intra-annual variation of WFP has been observed for several crops including cereals, vegetables and apples (Zhuo *et al.*, 2016). This is an important drawback, as the WFP is only representative for the reported year, while the decision-making process requires long-term and more robust serial historic data, which is not always available (Liu *et al.*, 2017). Under typical Mediterranean climate conditions, WFP values are thus expected to vary with the highly variable rainfall (green water) and irrigation needs (blue water) (*e.g.* 30-100% from year to year). This is in line with Vázquez-Rowe *et al.* (2012), who emphasized the impact of the harvest year when reporting the environmental impact of wine production and the need for including a timeline analysis in the wine sector. To minimize such a variation, the WFP estimation has been standardized by the ISO norm 14046 (ISO, 2014; Lovarelli *et al.*, 2016). The LCA is another standardized methodology to assess environmental burdens of a product from its production to its disposal or recycling (cradle-to-grave approach) according to the ISO standard 14040 series, (ISO, 2014) and it has been used to characterize the wine supply chain (Neto *et al.*, 2013; Quinteiro *et al.*, 2014). Neto *et al.* (2013) identified four stages of wine production with relevant environmental impact: viticulture, wine production (winemaking to storage), wine distribution and bottle production. Nevertheless, the LCA approach can fail to truly represent environmental impacts related to water and WW management (Comandaru *et al.*, 2012) and an improved temporal resolution (*e.g.* more frequent assessments in time) is needed to attain correct conclusions based on LCA of crop production (Pfister and Bayer, 2014). This must be tested for grape and wine production.

STRATEGIES TO IMPROVE WATER USE AND WASTEWATER MANAGEMENT IN THE VINEYARD AND WINERY

In order to minimize WW production, several strategies can be adopted to save water in the vineyard and in the winery. We further describe different approaches in the context of Mediterranean wine production.

Strategies for the vineyard

Water saving and water protection strategies in the vineyard may include short and long-term approaches. On the short-term, more efficient irrigation practices (*e.g.* deficit irrigation) and more precise irrigation scheduling can minimize the negative impacts of climate change on viticulture in South Mediterranean countries and help to save water (Chaves *et al.*, 2010; Iglesias and Garrote, 2015; Medrano *et al.*, 2015; UN-WATER, 2015) (Table I). Literature reports differences in water use efficiency by different grapevine genotypes, which should be considered for irrigation management purposes (Costa *et al.*, 2016). The use of locally adjusted crop coefficients (Kc_{adj}) in deficit irrigation, derived not only as function of soil and climatic conditions and agronomic practices (Allen *et al.*, 1998; Myburgh, 2016), but also as function of genotype, phenological stage, differences between canopy size, row orientation, training system, vine spacing and different levels of soil water or salinity stress or specific floor management practices (*e.g.* surface mulching or the use of cover crops), will enable an accurate determination of the adjusted (or actual) crop evapotranspiration (ETc_{adj}) (see Allen and Pereira, 2009 and Pereira *et al.*, 2015 for a detailed general review). Also, the use of the “dual” Kc approach, that splits the Kc into the algebraic sum of a basal crop coefficient (Kcb) and a soil evaporation coefficient (Ke), and allows to separately account the contribution of soil evaporation (E) and grapevine (and cover crops, when present) transpiration (T) to the actual ETc (Allen *et al.*, 2005; Farahani *et al.*, 2007; Fandiño *et al.*, 2012; Cancela *et al.*, 2015; Ferreira *et al.*, 2017), should be envisaged in order to better manage irrigation with water savings and decreased leaching risks. In fact, soil management practices (*e.g.* mulching) can minimize soil evaporation and help to control excessive soil temperatures (Dalmago, 2004) and promote soil fertility and water infiltration (Keller, 2015; Medrano *et al.*, 2015). Moreover, the use of low competition species and adequate management of cover crops, together with installation of water basins to retain winter’s rainwater, can promote water infiltration and increase water availability during summer period. Flowmeters in different sectors of the vineyard can help to quantify water use and improve water inputs' inventory. Breeding and selection of varieties, clones and rootstocks with higher resistance to water and heat stress can also contribute to water savings (Gonçalves and Martins, 2012; Keller, 2015; Carvalho *et al.*, 2019), though this is a typical medium to long-term strategy.

Meanwhile, another very important component for sustainable water use in wine production is the precise application of PPP, as well as the management of related WW_{PPP}. Several techniques can reduce spray drift pollution from pesticide spraying in agricultural systems, as explained by Otto *et al.* (2015). A 38% reduction in drift pollution (*e.g.* using low-drift nozzles), up to a maximum of 98% reduction could be achieved if hedgerows co-occur alongside fields (EU Commission, 2016). The use of low or anti-drift equipment and techniques are thus recommended to be included in environmental regulatory programmes on a regional scale (OECD, 2014; Otto *et al.*, 2015). In addition, more precise knowledge on vineyard canopy architecture (height, width, volume, density and exposed leaf area) can help to optimize PPP and fertilizer treatments (Rosell and Sanz, 2012; Gil *et al.*, 2014). The wider use of wastewater collection infrastructures in the vineyard or evaporation of water from remnants in dehydration systems (Doruchowski *et al.*, 2014) will also help to minimize WW pollution.

Strategies for the winery

Monitoring plan for winery wastewaters

Water use in the winery represents the smallest part of water inputs for wine production, considering production of grapes under irrigated conditions. However, WW_{winery} production can have a major environmental impact (Christ and Burritt, 2013). The first step consists in a self-assessment program to compile existing data on water use, water quality, WW_{winery} sources and respective physical-chemical quality. This will help to identify hotspots and report gaps to prepare further assessment. It will also open the possibility to hierarchize winery operations in terms of water needs, contribution for WW_{winery} flows and organic loads. The monitoring plan should account the specific activities of Period I and Period II. The WW_{winery} treatment solutions should be adapted to fluctuations of volumes and loads, allowing an efficient removal of contaminants during the peak season. Because the organic matter content present in WW_{winery} is highly soluble and biodegradable, mainly during Period I, biological treatment systems are technically possible for this type of WW_{winery} (Oliveira *et al.*, 2009; Mosse *et al.*, 2011; Da Ros *et al.*, 2016). Development and use of effective and cheaper alternatives for WW_{winery} treatment is crucial to small/medium wineries to accomplish legal requirements for recycling or disposal (GWRDC, 2011). Cost-effective options for WW_{winery} recycling/disposal must rely on higher energy efficiency and low maintenance costs (Mosse *et al.*, 2011; Oliveira and Duarte, 2015; Kyzas *et al.*, 2016).

Winery wastewater recycling/disposal

In order to reduce costs with WW_{winery} recycling, there are some strategies to be implemented. For example, if the ultimate aim is to reuse treated WW_{winery} for irrigation purposes, domestic WW should not be combined with WW_{winery}. This will prevent contamination by bacteria, viruses and parasites, which require further treatments and a disinfection step. Moreover, the guidelines available for WW_{winery} reuse, in Old World Viticulture countries, include mainly microbiological parameters (Brissaud, 2008; Oliveira and Duarte, 2016). Regarding WW_{winery}, inorganic parameters are of particular concern; the sodium adsorption rate (SAR) is recommended to be below 6 $mmol^{1/2}$ $L^{-1/2}$, to prevent adverse soil structural changes (Laurenson *et al.*, 2010). To reduce SAR, some strategies should be applied in the winery (Kumar and Christen, 2009; Mosse *et al.*, 2011), namely the reuse of washing water. The use of alternative cleaning agents based on potassium hydroxide and magnesium hydroxide, although more expensive, may be an option. The ozone treatment as a disinfection procedure will allow the decrease of the conductivity and COD, thus contributing to attain the compliance of the legal limits for uses in crop irrigation (Lucas *et al.*, 2009; Cullen and Norton, 2012). The reduction of COD can also be achieved by screening out solids larger than 0.5-1.0 mm with basket screens and by reducing the contact period between solids and WW, minimizing mass transfer. The replacement of citric acid by phosphoric acid is also an advantage (Brissaud, 2008). According to the World Health Organization recommendations for WW reuse (WHO, 2006), the amount of organic matter to be applied via irrigation should not exceed 500 mg L^{-1}, expressed as BOD5, to avoid changes in soil properties (EPA, 2004). The same source states that application of an urban WW containing a BOD5 between 110-400 mg L^{-1} may be beneficial for crops (WHO, 2006). However, countries with more restrictive legislation only allow the use of WW with 20-30 mg L^{-1} of organic matter expressed as BOD5 (Tsagarakis *et al.*, 2004; Brissaud, 2008). Recent Portuguese legislation sets maximum values of 10-40 mg L^{-1}, expressed as BOD5, for wastewater reuse in crop irrigation, according to quality classes (DL 119/2019). Also, the physical-chemical analysis could be insufficient to evaluate the potential ecological risk, since it does not allow the assessment of possible combined effects of different contaminants mixed together, as well as their bioavailability. Therefore, bioassays are recommended for ecological risk assessment of WW relative to soil or other matrices, whenever WW should be used as an organic amendment (Oliveira *et al.*, 2009; Mosse *et al.*, 2011).

Integrative strategies for a more sustainable wine production chain

The wine industry needs improved water metrics and integrative management strategies related to water fluxes in the vineyard and in the winery. To deal with water scarcity in the Mediterranean region, rain harvesting can be considered, furthering the water supply to the vineyard (Stec and Zeleňáková, 2019). In addition, a conceptual overview of the existing water and WW flows along the wine production chain (vineyard and winery phases) should be envisaged, considering the "Farm-Winery" scenario, which is typical in regions such as Alentejo (Figure 3). Two distinct WW treatment approaches are proposed: the first relates to vineyard's WW (WW_{PPP}) generated by the activities (*e.g.* crop protection) taking place in the vineyard, whereas the second is related to WW$_{winery}$ (Figure 3). Consequently, we consider two WW treatment plants in this analytical approach: an agrochemical dedicated WW treatment plant (AWWTP) and an industrial WW treatment plant (IWWTP) (Figure 3).

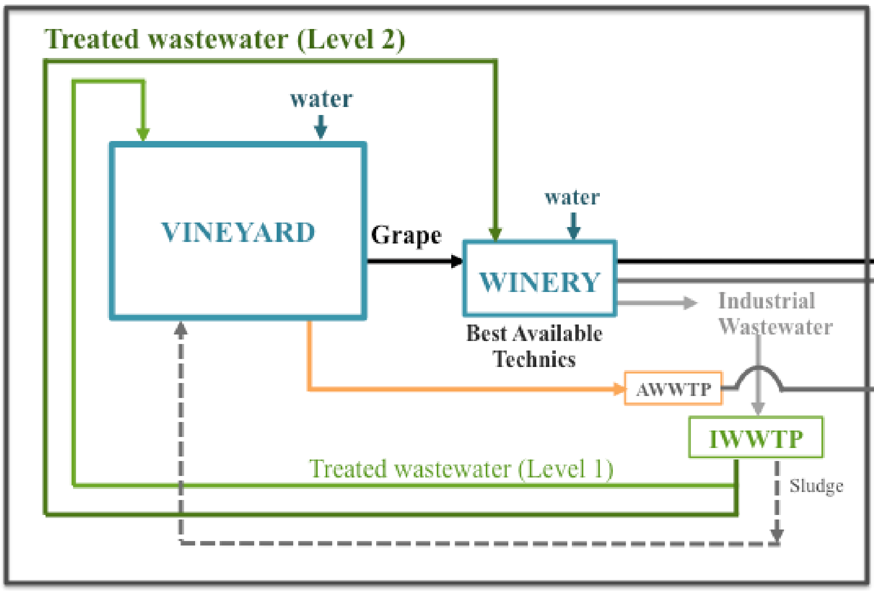

Figure 3. "Farm-Winery" conceptual approach to improve vineyard and winery environmental management of water inputs and generated wastewater (WW) in the vineyard (WWW$_{PPP}$) and in the winery (WW$_{winery}$). **Black arrows** indicate raw material and final product. **Blue arrows** indicate fresh water flows and **green arrows** represent WW$_{winery}$ with different quality levels (Level 1 – improved quality & Level 2 – low quality). The **orange arrows** represent **WW$_{PPP}$ flows** and the **dark grey** dotted lines are WW flows. **AWWTP** – Agrochemical dedicated WW$_{PPP}$ Treatment Plant; **IWWTP** – Industrial WW$_{winery}$ Treatment Plant.

Abordagem conceptual do tipo "Farm-Winery" para melhor gestão ambiental da vinha e da adega em termos da origem do recurso água e das águas residuais geradas (WW), na vinha (WW$_{PPP}$) e na adega (WW$_{winery}$). As setas a ***cor negra*** *indicam matéria-prima e produto final, enquanto as* ***setas a azul*** *indicam os fluxos de água doce do recurso água (input). As* ***setas verdes*** *representam WW com diferentes níveis de qualidade (Nível 1 - qualidade melhorada e Nível 2 - qualidade baixa). As* ***setas a laranja*** *representam água residual tratada com origem em pesticidas e seu uso (WW$_{PPP}$) e as linhas a tracejado e* ***cinza escuro*** *representam fluxos de WW.* ***AWTP*** *– Estação de tratamento de agroquímicos dedicada a águas residuais;* ***IWWTP*** *– estação de tratamento industrial de águas residuais.*

Optimal water management in the winery must identify flows and loads as part of the working Periods I and II, as well as be a function of the type of grape processed (red *vs.* white grapes). This allows for segregation of flows and selection of the most biodegradable in order to improve WW$_{winery}$ quality (Level 1 quality), which can be recycled within the winery, namely to wash the floors. In parallel, low quality water flows (*e.g.* with lower biodegradability and high polyphenol content) (Level 2 quality) are suggested to be used after being treated, to irrigate landscape crops surrounding the wineries or the vineyard, or as a small additional supply to vineyard's irrigation. Rain harvesting is another option to consider for reducing water consumption in wineries. It's worth noting that such decisions do require a previous cost-benefit analysis in order to ensure the economic viability and potential new projects.

More integrative approaches to optimize the implementation of climate change adaptation measures in viticulture and to optimize water use in the wine production chain should consider closer interaction and information exchange between all stakeholders (growers, winery managers, technical advisors, local and regional institutions, as well as government entities). A more efficient water management will be achieved when water metrics accommodate data from vineyards, up to the whole region and related governance.

CONCLUSIONS AND FUTURE PROSPECTS

Water must be protected and efficiently used, especially in dry areas. This paper provides a resumed overview and discussion over the water use and WW management in viticulture and oenology in South

Portugal. This review helps to clarify and emphasize existing limitations concerning water issues (*e.g.* efficiency, metrics) in wine production in dry regions and suggests possible approaches to optimize water and WW management in vineyards and wineries.

The typical inter-annual climate variability of Mediterranean climates and more extreme climate events offer increasing challenges when estimating water needs and water use in irrigated vineyards. Indeed, water consumption can be highly variable in the field (due to climate conditions), but also in the winery. In this case, the size of the winery, the type of wine produced and the winemaking periods (I and II) are important variation factors.

Simple water and WW indicators to be used in vineyards and wineries were highlighted and should contribute to: 1) optimize water and WW management in irrigated vineyards in dry areas such as Alentejo (Portugal); 2) optimize water and WW management in the winery; 3) support improved water management in accordance to the specificities of the wine production chain, and ultimately 4) minimize the potential environmental impact of the wine industry. Future studies should test the potential combination of water stress/water scarcity indicators with other analysis tools (*e.g.* WFP and LCA) to support the wine industry in assessing its environmental impact at farm and regional levels. Indicators such as Carbon Footprint or Ecological Footprint should complement studies focused on water use and WW production in the wine sector. Sustainability and certification programs must consider the water component in both the vineyard and winery, especially in dry areas. These initiatives improve stakeholders' perception of sustainability issues and sustainability certification, which require robust water metrics and data reporting. Still, analysis of medium to long-term impacts of WW on crop and soil needs more detailed studies, particularly for wine production under dry and warm climates.

ACKNOWLEDGMENTS

We thank to Fundação para a Ciência e Tecnologia (Portugal) through the research unit UID/AGR/04129/2013 (LEAF). J. M. Costa and Carlos Lopes also acknowledge the support of the EU project NEFERTITI (EU Horizon 2020, grant agreement No. 772705), Network 8 – Water Use Efficiency.

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