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Implementing Nature-Based Solutions for Treatment of Winery's Wastewater and Sustainable Carbon-Footprint Reduction

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Nature-based solutions can reduce the negative effects of climate change by mitigating the risk of droughts with water retention, increasing infiltration, controlling stormwater runoff and by decreasing atmospheric greenhouse gas emission. The carbon footprint of wastewater treatment plants is significant; the processes are energy-intensive and thus high CO_2 emitters. The technology of wine making creates wastewater with extremely high organic content and is coupled with high carbon footprint. Its treatment poses challenges for wastewater plants. This study focuses on the wastewater of winemaking process and its negative effects on carbon-footprint and the wastewater management opportunities of the Csengőd wastewater treatment plant in Hungary. The traditional wastewater treatment and the potential implementation of a poplar plantation were assessed economically and environmentally. The energy consumption and the carbon footprint reduction were compared in the two cases to evaluate their sustainability. Significant energy savings and economic benefits can be achieved by the trade-off between traditional treatment and the use of nature-based solutions. The assessment is novel, because it evaluates all three sustainability pillars, considering: benefits with pay-off through technological processes, environmental aspects and additionally the interests of stakeholders.
A poplar plantation can be used to pre-treat wastewater of a winery and thus effectively reduce the high organic concentration – thereby protecting the sensitive technologies of traditional wastewater plants. The trade-off results in annual energy savings of 61,823 kWh and CO_2 emission reduction of 16,692 kg, which means financial savings. The direct sustainable benefits are € 287,824 over the 50-year life cycle in a small wastewater plant.

1. Introduction

The negative effects of climate change already affect the Great Plains of Hungary. Desertification has now become a tangible reality accompanied by declining soil moisture and decrease of surface and groundwater resources (Kis et al., 2025). In addition, various pollutions, infrastructural deficiencies, and inadequate recycling of wastewater also hinder efficient water management. Water utilities face serious challenges in efficiently managing wastewater, as they require proper treatment before released back into natural water bodies (Subramanian and Suresh, 2024). Treated wastewater can be a potential source of irrigation but proper cleaning is an energy-intensive process. Retaining cleaned wastewater may reduce drought and contribute to sustainable water management (Kaur et al., 2022).
Agricultural activity is extensive in the Great Plain and plays a prominent role in food security. Vineyards and winemaking are found at many locations, which is largely due to the favourable natural environment. The sandy soil, abundant sunshine and mild climatic conditions are ideal for vineyards (Anastasiou et al., 2023). Kunság wine region in the Great Plain is the largest in Hungary, accounts for 53.62 % of domestic wine production in 2024 (HNT, 2024). Viticulture and winemaking have a centuries-old tradition and is a key economic, and cultural activity. However, winemaking - the fermentation-based alcohol production process - and other winery processes generate an exceptionally high organic content of the resulting wastewater. This has a significant environmental impact as e.g. 1 L of alcohol results in 8-18 L of wastewater - for wine this ratio is 1-to-4 L - with

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high organic load due to their significant protein and carbohydrate content (Celso et al., 2025). Although phosphorus is not directly part of the winemaking process, its presence in grapes can influence the chemical composition of must and wine, contributes to grape quality, and thus to its essence. Phosphates are essential nutrients of yeasts by supporting their metabolism, that accelerate fermentation and contribute to the efficiency of alcohol production. On one hand, phosphorous provides optimal conditions for fermentation and so for the quality of wine, but on the other hand, it is a large contributor of organic concentration in wastewater. The biochemical oxygen demand (BOD) of this effluent may exceed 30 g/L, which is about 2-orders of magnitude above the typical - and legally permitted - standard values. In addition, during cleaning of winery equipment, phosphorus-containing residues, detergents and other metals can also enter wastewater (Biacs, 1997).
The industrial wastewater of Kiss és Társai Kft. (Kiss Ltd.) is currently delivered untreated to the Csengőd wastewater treatment plant (WTP) in the Kiskun wine region with high organic content in pressurized pipes. The high BOD level of this wastewater imposes heavy stress on the WTP, by the extreme load on treatment technologies. This leads to higher energy demand, increased greenhouse gas (GHG) emissions, and higher operational costs. This study evaluates a possible nature-based solution (NbS) - a poplar plantation - as a pretreatment of wastewater arriving from winery. This approach is compared to existing, conventional treatment at Csengőd WTP to assess the reduction capabilities of the organic load of wastewater before reaching the WTP. As a result, energy consumption can be reduced - by lower energy demand of aeration pumps -, which means lower carbon-footprint - as environmental impact -, lower operation costs - as economic impact, and enhancing sustainable water management along with increased water resources in the region - as social impact.
The poplar plantation as NbS is compared to the currently used traditional wastewater treatment process in a direct energy-audit (DEA), life-cycle assessment (LCA), and a combined cost-benefit analysis (CBA) with life-cycle-cost analysis (LCCA). The analysis considers all three pillars - environmental, social, economic - of sustainable development goals by quantifying energy savings, carbon footprint, cost of CO_2 neutralization and cost-effectiveness over the 50-year life cycle. This research assesses the possible benefits of poplar plantations as NbS over traditional wastewater treatment strategy at Csengőd WTP for high organic content of winemaking by a multi-pillar, innovative, lifetime monetarization of climate change costs through CO_2 neutralisation.

2. Background and Site Description

The Kunság wine region - the largest wine region in Hungary - is in the Great Plain. Settlement Csengőd (Figure 1.) is located in the north-western part of the area, close to the Danube.

Figure 1: Location of Kunság wine region and Csengőd wastewater treatment plant (Ercsey, 2025)

The sandy-loess soil, the lowland character and the dry climate make it suitable for agricultural - viticulture - activities. The annual rainfall in the area is 550-570 mm (H_{prec}), of which 310-330 mm falls during the vegetation period. The water supply is sparse, the area is generally water-deficient, water shortage makes efficient water use critical, therefore water resource management has key importance. The Kiskunsági-Víziközmű Szolgáltató Kft. (Kiskunvíz) is responsible for the public utilities of Csengőd. In addition to providing clean and healthy drinking water, the company is also responsible for the proper treatment of wastewater and the protection of local water resources. The technology used greatly influences the condition and the environmental compatibility of treated wastewater that is returned to nature, thus how it contributes to the ecological balance of the Great Plain areas (Kiskunvíz, 2024). Kiskunvíz operates a separated sewer network, and wastewater is moved via gravity and pressurized pipes to WTP, which treated 263,170 m^3 of wastewater in 2023. The wastewater arriving at the plant flows through screening, grease and sand separators, swamp, where the wastewater is mechanically pre-treated. This is followed by biological treatment, which uses a SBR system (Sequencing Batch Reactor, Figure 2.), batch operation technology. The wastewater is treated in 1 reactor but in 4 phases: aeration, mixing, sedimentation, decantation (drainage and wastewater removal). After biological treatment, the wastewater can be safely discharged into the receiving watercourses, complying regulations. The biggest advantage of SBR systems is their operational flexibility, as the different phases are carried out in a single reactor, which reduces the required volume. SBR systems are well suited for use in municipalities or industrial facilities where the water load is variable or seasonal. The energy requirements and costs of SBR systems are generally lower than those of continuous systems, especially when wastewater load is lower, however, the higher organic content causes higher energy demand due to the aeration pumps' operation. The higher organic concentration of wastewater from wineries requires special treatment, which is challenging for the WTP.

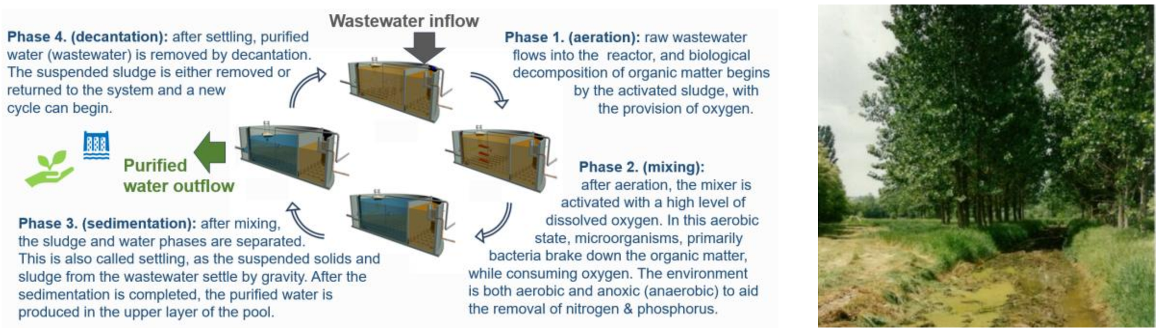

Figure 2: Wastewater treatment phases in an SBR system (left), poplar plantation (right) [source: Kiskunvíz]

The winery of Kiss Ltd. operates 260 days/y, so the average effluent inflow at WTP of Csengőd is 50 m³/day ($V_{waste,daily}$) (Table 1), which is approx. 5 % of the total incoming volume.

Table 1: The volume of technological wastewater from the wine factory by its place of origin (Kiskunvíz)

	Process of winemaking	Wastewater output	Notes
1	Washing of glasses	5 x 10^3 m^3/y	0.5-1 L water & wastewater per 1 L of wine
2	Wine making activity	1 x 10^3 m^3/y	0.5-1 L water & wastewater per 1 L of wine
3	Wine cellar activities	1 x 10^3 m^3/y	2-4 L water & wastewater per 1 L of wine
4	Washing of outdoor tanks	3 x 10^3 m^3/y	0.2-0.5 L water & wastewater per 1 L of wine
5	Bottling (bottle rinsing)	5 x 10^3 m^3/y	1-3 L water & wastewater per 1 L of wine
	Total:	1.3 x 10^4 m^3/y	average 50 m^3 daily (with 260 days of operation)

The wastewater of winemaking has significant organic content at Kiss Ltd. ($BOI_{WTP,wine}$ = 5,284 mg/L compared to WTP incoming average $BOI_{WTP,avr}$ = 433 mg/L in 2024), which varies with different production processes, applied technologies and seasonal factors. Biological wastewater treatment is one of the most common methods for treating these wastewaters. During the process, microorganisms (bacteria, fungi) decompose organic matter. It can take place with the addition of oxygen (aerobic, Eq.1) or in an oxygen-free environment (anaerobic, Eq.2). Aeration requires pump-operation, which has high energy demand and thus CO_2 emission.

$$C_xH_yO_zN + O_2 \rightarrow CO_2 + H_2O + NH_3 + biomass \quad (1)$$

$$C_xH_yO_z \rightarrow CH_4 + CO_2 + H_2O \quad (2)$$

The organic content of wastewater is assessed by the biochemical oxygen demand (BOD). BOD determines the amount of dissolved oxygen (in mg/L) required for the decomposition of all organic content in wastewater in aerobic oxidation. During this process, bacteria cover their energy needs by decomposing organic matter, while the oxygen is supplied to the reactor by radial pumps that drastically increases operating costs. The amount of oxygen required for the decomposition of organic matter, and thus the high energy demand of pumps, can be reduced by using natural solutions. Applied solutions in wastewater pretreatment include the constructed aquatic plant system, the sand-soil-reed filter field, and the wastewater irrigation system (Bodik and Ridderstople, 2007). These methods use nature's self-cleaning processes to treat wastewater, while minimizing energy consumption and environmental impact. In Hungary, poplar plantation is a proven "tree plantation irrigation system" (Figure 2, right), which can be used to treat wastewater from the food and wine industries. Wastewater is valuable as water source and as a nutrient source for plants, while rotational flooding of the forest's ditch ensures the continuous operation. Organic molecules enter the soil where microorganisms break them down, meanwhile the water and nutrient component promote more rapid biomass formation of poplar. In the first year, biomass formation can reach 8-10 t/ha of dry matter, and after 3-4 years, it can be up to 20–40 t/ha. The poplar irrigation greatly reduces BOD, contributes to the preservation of natural forests, while the additional yield generates environmental and economic benefits. With proper flooding, the seeping water will be clean, thereby contributing to sustainable water management. During the winter, the ditches are flooded less frequently - usually every 2-3 weeks -, so that the frozen wastewater melts and infiltrates into the soil until the next irrigation.

3. Method

The methodological framework of the study is based on the comparison of two wastewater treatment scenarios:
(i) the current practice of conventional mechanical aeration treatment at the Csengőd WTP, and
(ii) an alternative system that includes a poplar plantation as a pre-treatment stage to reduce the organic load of the winery wastewater before it enters the WTP.

Pre-treatment processes consider the seasonal fluctuations of the winery wastewater, especially the increased volumes during harvest period from August till November. Winery wastewater has large impact on the operation of the WTP, and the environment. Therefore, a pre-treatment system can protect the WTP on one hand and improve economic and environmental sustainability on the other. E.g. the pre-treated winery wastewater can be used for irrigation - which is particularly beneficial in water-scarce areas-, while contributing to circular economy by improving water resources, and the social interest. In case of wineries, green infrastructure plays a special role in the management of wastewater and by-products - with high organic and nutrient content-, which is optimal for the operation of poplar plantation. The use of these NbS for pre-treatment is sustainable, creates multiple benefits and competitive advantages (Csete, 2023). The analysis of this paper focuses on a winery effluent - from Kiss és Társai winery - with high organic content, discharged to the Csengőd WTP. The energy demand of the aeration in the treatment process is highlighted, as this phase accounts for the largest share of electricity consumption and thus carbon dioxide emission. The energy demand of aeration is assessed by a combined direct energy-audit (DEA) and life-cycle assessment (LCA) and compared to the achievable energy savings with the use of a poplar plantation as NbS. Using plant operation data and literature findings, the aeration energy demand was estimated at 0.9-1.0 kWh per kg BOD (ED_{aer}) removed at Csengőd WTP, based on daily inflow volume and process principles. Studies report values between 0.2-2.0 kWh/kgBOD, and the estimates for Csengőd WTP are in the middle (Siatou et al., 2020). The plant's average monthly energy demand is 20,882 kWh between January and July, and 31,396 kWh between August and November. High organic wastewater from winery operation increases energy use by over 50 %. In the existing scenario, this is converted to total energy in kWh and to monetary value in EUR for financial assessment (DEA method) as well as to kg of CO_2-emission for environmental impact assessment (LCA method). The alternative scenario shows the possible reduction of aeration energy (ΔE_{aer}) which was estimated based on the removal capacity of the poplar plantation.

$$\Delta E_{aer} = BOI_{WTP,i} \cdot ED_{aer} \cdot V_{waste,daily} \quad (3)$$

Equation 3 is used to calculate the achievable energy saving with lower pump operation times. The value of wastewater $BOI_{WTP,i}$ varies based on the operating environment; monthly average due to winery operation is $BOI_{WTP,wine}$ = 5,284 mg/L, while average WTP inflow is $BOI_{WTP,avr}$ = 433 mg/L. The discharge of winemaking wastewater to poplar plantation is often combined with the use of a flotation, where $BOI_{WTP,flot}$ = 2,500 mg/L.

$$\Delta F_{CO2} = (E_{scen,2} - E_{scen,2}) \cdot EF_{aer} \quad (4)$$

The carbon-footprint reduction (ΔF_{CO2}) can be calculated using Equation 4 of the two aeration energy demand scenarios ($E_{scen,i}$). The emission factor (EF_{aer}) is 0.27 kg_{CO2}/kWh and the neutralization cost is 0.07 EUR/kg_{CO2} (IEA, 2024). When implementing poplar plantation, local soil conditions shall be considered to avoid potential environmental damage from winery wastewater entering the soil. From hydrological aspect, the depth and quality of the groundwater were determined by linear interpolation using data from groundwater monitoring wells located in the surrounding settlements. The calculated maximum groundwater level is 99.20 m a.MSL, while the height of the planned poplar area is 101.65 m a.MSL. The required area for drainage considers the maximum groundwater level to avoid the risk of pollutant infiltration. However, a continuously operating monitoring system is necessary to observe the quality of the drained wastewater and the condition of the soil and groundwater. The required area (A_{poplar} [m^2]) of the poplar plantation, the minimum required area for organic matter load (A_{load} [m^2]) and the acceptable water cover (W_{cov} [mm/y]) can be determined using Eqs. 5, 6, and 7.

$$A_{poplar} = (Q_{year} \cdot B \cdot Y) / (T \cdot N) \quad (5)$$

where Q_{year} is the annual wastewater volume [13,000 m^3]; Q_{daily} is the daily wastewater volume [50 m^3]; B is the specific content value [50 g/m^3]; Y is the utilization efficiency [0.6]; T is the typical yield of poplar [8,200 kg/ha]; N is the required nutrient uptake for 1 kg of plant [0.073 kg/kg].

$$A_{load} = (BOI_{inflow} - BOI_p) \cdot Q_{daily} / OC \quad (6)$$

where BOI_{inflow} is the wastewater flowing into the poplar site [2,500 g/m^3 or 5,284 g/m^3], BOI_p is the permissible amount of wastewater filtered through the soil [0 g/m^3], OC is the oxidizing capacity of soil [sand, 10.0 g/m^2*day].

$$W_{cov} = Q_{year} / \max(A_{poplar} \,;\, A_{load}) + H_{prec} \quad ;\ \text{where} \max \mathrm{Wcov} \leq 5{,}000\ \mathrm{mm/y} \quad (7)$$

For financial assessment, a combined economic-environmental method ($NPV_{lcca,cba}$) was used (Eq.8) to include (i) capital investment, maintenance and reforestation costs of poplar plantation in a life-cycle-cost analysis (LCCA) in a 50-year horizon and (ii) the cost-operation-maintenance savings from reduced energy consumption of pump operation and neutralization costs due to lower CO_2 emission in a cost-benefit analysis (CBA).

$$NPV_{lcca,cba} = I + \sum_{1}^{t} \frac{OP \cdot (1+p)^{t-1} + MR}{(1+i)^t} + \sum_{1}^{t} \frac{R_{popl}}{(1+i)^t} \pm \sum_{1}^{t} \frac{ACI_k}{(1+i)^t} \pm \sum_{1}^{t} \frac{NCO2_t}{(1+i)^t} - \frac{C}{(1+i)^t} \quad (8)$$

where I is the initial implementation cost; MR is the annual maintenance and repair cost; R_{popl} is the revenue from poplar logging minus the cost of replanting; OP is the starting annual operation cost; C is the life-end restoration cost of the area; i is the interest rate for refinancing (3.0 %/y); p is the price increase, the inflation rate (2.0 %/y.); t is the lifespan (50 y); ACI_k is the annual additional charge or incentive by the state (+ if grant; - if tax); $NCO2_t$ is the annual CO_2 neutralization and/or absorption cost (+ if neutralization; - if absorption).

4. Results

The average daily value of wastewater from winery operation has high oxygen demand, $BOI_{WTP,wine}$ = 5,284 mg/L. Direct release of such wastewater into the environment is irresponsible and can lead to serious environmental problems, such as drastic decrease in the oxygen concentration of receiving waters, rotting, fish death, intense odour effects, and eutrophication. Latter is a process during which enrichment of surface waters with nutrients occur and thus, this is one of the most serious environmental problems of our time.
The daily and annual energy demand of aeration in the 3 scenarios as summarized in Table 2., including the CO_2 neutralization costs, using Eq.3 and Eq.4. The electricity price is 0.21 €/kWh.

Table 2: Energy demand of aeration pump operation and carbon-footprint reduction – daily/annual

	Current practice ($BOI_{WTP,wine}$ = 5,284 mg/L) (i) energy demand of aeration (ii) carbon-footprint of aeration	Combined poplar & flotation ($BOI_{WTP,wine\text{-}flot}$ = 2,784 mg/L) (i) energy demand of aeration (ii) carbon-footprint of aeration	Combined poplar plantation ($BOI_{WTP,poplar}$ = 0 mg/L) (i) energy demand of aeration (ii) carbon-footprint of aeration
i)	237.78 kWh / 61,823 kWh	125.28 kWh / 32,573 kWh	0 kWh / 0 kWh
ii)	64.20 kg_{CO2} / 16,692 kg_{CO2}	33.83 kg_{CO2} / 8,795 kg_{CO2}	0 kg_{CO2} / 0 kg_{CO2}
i) cost	€ 49.93 / € 12,983	€ 26.31 / € 6,840	€ 0 / € 0
ii) cost	€ 4.49 / € 1,168	€ 2.37 / € 616	€ 0 / € 0

The current conventional approach - lacking any pretreatment solutions - requires annually 61,823 kWh energy for aeration which emits 16,692 $kgCO_2$. Implementing the poplar plantation - either combined with a flotation or operating independently - energy demand and carbon-footprint can be reduced to 32,573 kWh and 8,795 $kgCO_2$ annually in case of a poplar-flotation operation and to 0 kWh and 0 $kgCO_2$ in case of poplar plantation only. Thus, the annual reduction in CO_2 emission may reach 16,692 $kgCO_2$, while the energy saving 61,823 kWh. Financially, the savings on these two together is 14,151 €/y, discounting the pump operation cost of aeration and carbon-neutralization over the 50 y life cycle sums up to € 287,824 without price increase. When an average of 2.0 % price increase is considered throughout the period, the discounted value increases up to € 546,271.
The required size of the poplar plantation for the reliable operation can be calculated using Eq.5 and 6. The standard required area is 6,515 m^2 and the minimum area to uptake the organic load is 5,000 m^2, which is smaller than the standard required area, therefore the minimal poplar plantation size is approx. 6,515 m^2. Considering a minimum 6 m x 6 m space for each tree, the least number of trees is 180. Evaluating the plantation for the acceptable water cover depth, Eq.7 show that sandy area is suitable, W_{cov} = 2,550 mm < 5,000 mm.

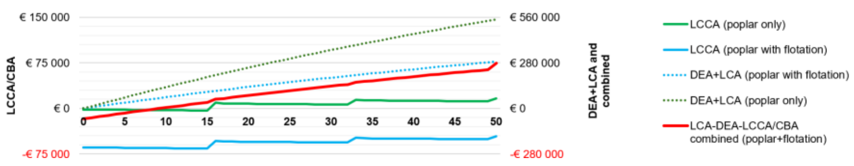

Figure 3: Economic and financial benefits and assessment of various poplar-flotation implementation scenarios

The LCCA study (Figure 3., green line) examining the implementation of the 0.65 ha poplar plantation by itself has a positive NPV of € 16,367. This can be achieved by poplar plantation, harvesting and replanting. However, considering the environment of the poplar plantation, the condition of the soil and the quality of groundwater, the safe operation of the poplar plantation requires the installation of a flotation device that can regulate the organic matter content of inflow wastewater. The NPV of this scenario (poplar + flotator) according to the LCCA-CBA is slightly negative, -€ 46,133 (Figure 3., blue line). The creation of a poplar plantation has environmental-economic-social impacts directly through the poplar plantation, but also indirectly, as it reduces the energy demand for pump operation (DEA method) and thus CO_2 emissions (LCA method). The achievable energy saving and CO_2 reduction were examined in the scope of a poplar plantation with or without the installation of the flotator. Earlier intervention has NPV of € 287,824; the latter has € 546,271. Combining the methods, and considering all benefits, advantages and costs, the total NPV is € 278,229 (Figure 3., red line). The implementation of a sustainable, NbS wastewater treatment is beneficial from environmental and social perspective and advantageous economically, resulting an average profit of nearly 500 €/month for 50 y.

5. Conclusions

This research creates a beneficial methodology for both climate change mitigation measures and proper treatment of industrial wastewater, while reducing the current drought problems and WTP organic overload. Winery wastewater using poplar plantation for pretreatment as NbS can significantly reduce organic matter stress for WTPs while reducing energy demand by 61,823 kWh annually and thus operating-maintenance costs. Additionally, it can decrease the environmental impacts of winemaking and the annual CO_2 emission by 16,692 kg. The value of these measures is equivalent to € 287,824 over the investigate 50 y life cycle. Beyond economic gains, the implementation of NbS has positive impacts on sustainable development, preserves water resources, improves stakeholder cooperation and promotes biomass production. Properly designed NbS can be economically, environmentally and socially beneficial, and their broad implementation can be facilitated by raising awareness and providing appropriate economic incentives - particularly in water-scares regions.

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