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Review

Wastewater disposal to landfill-sites: A synergistic solution for centralized management of olive mill wastewater and enhanced production of landfill gas

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ABSTRACT

The present paper focuses on a largely unexplored field of landfill-site valorization in combination with the construction and operation of a centralized olive mill wastewater (OMW) treatment facility. The latter consists of a wastewater storage lagoon, a compact anaerobic digester operated all year round and a landfill-based final disposal system. Key elements for process design, such as wastewater pre-treatment, application method and rate, and the potential effects on leachate quantity and quality, are discussed based on a comprehensive literature review. Furthermore, a case-study for eight (8) olive mill enterprises generating 8700 m^3 of wastewater per year, was conceptually designed in order to calculate the capital and operational costs of the facility (transportation, storage, treatment, final disposal). The proposed facility was found to be economically self-sufficient, as long as the transportation costs of the OMW were maintained at ≤ 4.0 €/m^3. Despite that EU Landfill Directive prohibits wastewater disposal to landfills, controlled application, based on appropriately designed pre-treatment system and specific loading rates, may provide improved landfill stabilization and a sustainable (environmentally and economically) solution for effluents generated by numerous small- and medium-size olive mill enterprises dispersed in the Mediterranean region.

1. Introduction

Landfills are the most common form of waste disposal and the final step of the waste management hierarchy. Landfills, being relatively cheaper than other treatment/disposal alternatives, are used not only by developing but also by industrialized countries, such as US, Australia, UK and Finland (Laner et al., 2012). While the use of landfills is decreasing in many parts of the world, there are thousands of closed facilities and others that will be closed over the next 10–30 years (Laner et al., 2012). Landfill mining has been recently proposed as an alternative for resource recovery (Krook et al., 2012). These sites are also used for sustainable sludge management, where the anaerobic sludge compost can be used as a landfill cover and thus help to biologically oxidize organic compounds as well as methane, in the landfill gas (Cukjati et al., 2012).

The landfill sites were usually abandoned after closure (Robinson and Handel, 1993). However, European Directives 1999/31/EC and 2008/98/EC imposed post-closure care (aftercare) of the closed landfills in order to protect human health and the environment. The aftercare strategies involve basically the monitoring of gas/leachate emissions, of the receiving bodies (groundwater, surface water, soil), and the maintenance of the cover and leachate/gas collection systems, which is reviewed in detailed by Laner et al. (2012). Although at least a 30-year aftercare period is required by European Landfill Directive (CEC, 1999), it is hard to determine when to finish this period (Laner et al., 2011). Leachate quality (BOD/COD ratio), gas production rate, cellulose plus hemicellulose to lignin (CH/L) ratio, physical stability (post-closure settlement), biological/chemical stability are among the suggested indicators for termination of aftercare, each of which, however, might have limitations (Laner et al., 2011).

Leachate production and management is one of the major problems related to the environmental-operation of sanitary landfills (Tatsi and Zouboulis, 2002). Landfill-leachate, due to its

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problematic nature (high COD, salinity and low biodegradability due to high COD/BOD ratio, etc.) needs to be treated before its discharge. The most common and cost effective treatment method is the activated sludge (sequencing batch reactor) coupled with necessary pretreatment (Renou et al., 2008).

Landfill sites were usually designed to minimize the amount of water entering the system in order to prevent the groundwater pollution (Benson et al., 2007). However, with the improvement in the landfill management by use of modern composite liners and leachate collection systems, entering water can be used as an advantage to improve the microbial activity, to enhance the rate of organic waste decomposition and eventually decrease the long-term monitoring and maintenance period. Municipal solid waste (MSW) landfills are often operated as bioreactors. This is accomplished with leachate recirculation through the waste body. The process enables enhanced waste and leachate stabilization, and optimized biogas production (Benson et al., 2007; Reinhart et al., 2002; Komilis et al., 1999). In landfill bioreactors, apart from leachate recirculation, external water may be added to enhance anaerobic breakdown of refuse (Sponza and Agdad, 2004; Reinhart and Al-Yousfi, 1996; Sanphoti et al., 2006). Accordingly, it is hypothesized that controlled wastewater application, based on appropriately designed pre-treatment system and specific loading rates, may provide improved landfill stabilization and a sustainable solution for difficult to treat wastewaters, such as Olive Mill Wastewater (OMW). Despite that EU Landfill Directive prohibits wastewater disposal to landfills, leachate recirculation is permitted under some circumstances, in small islands and decentralized areas (JMD, 2006), where many olive mill enterprises exist in the Mediterranean Regions.

In this paper a case study is presented, dealing with the design and application of a landfill-based centralized facility, treating Olive Mill Wastewater (OMW). A conceptual design was performed and the capital and the operational costs of the overall facility (transportation, storage, pre-treatment, disposal) were calculated. While treating OMW via landfills, there are key points to be considered such as wastewater pre-treatment, application method and rate, effects on leachate quantity and quality. These issues are discussed in the present paper based on a comprehensive literature review, highlighting also future research needs.

2. Centralized management of olive mill wastewater

Olive mill wastewater is an effluent with high organic load (COD = 40–100 g/L), generated during the 2–3 months campaign of olive oil producing factories. It is a complex acidic effluent (pH 4.0–5.5), mainly composed of water (83–96%), sugars (1–8%), nitrogenous compounds (0.5–2.4%), organic acids (0.5–1.5%), phenols, pectin and tannins (1.0–1.5%), lipids (0.02–1.0%) and inorganic substances (Hamdi, 1993; Sayadi et al., 2000). Different technologies are available for olive mill wastewater (OMW) treatment, based on combination of physical, chemical and biological processes (Azbar et al., 2004; Mantzavinos and Kalogerakis, 2005; Paraskeva and Diamandopoulos, 2006). Indeed, fully equipped treatment systems for olive mill wastewaters incur total costs of 5–22 €/m^3 treated (Azbar et al., 2004). This is the case for biological treatment (anaerobic, aerobic) combined with necessary pre-treatment (physicochemical or mechanical). In case of natural evaporation systems the total costs are in the order of 0.65–1.31 €/m^3 (Azbar et al., 2004).

The most common treatment and disposal method for small and dispersed olive mill enterprises is natural evaporation in lagoons (Kavvadias et al., 2010). Lagoon performance is, however, significantly affected by wastewater characteristics and increasing wastewater solids and organics will decrease the evaporation rate (Jarboui et al., 2009). Additionally, they are often designed with large depth, thus wastewater evaporation is difficult to achieve in the field. It is therefore common practice that OMW ends up illegally to neighboring soils, groundwater, surface water bodies and/or the ocean. Another important problem of conventional open evaporation ponds is the generation of offensive odors all year round (Lagoudianaki et al., 2003). Yet, in addition to the potential biodegradation mechanisms taking place in the ponds and further production of the greenhouse gases, the loss of useful energy that can be gained through anaerobic digestion should also be considered.

Centralized management of olive mill wastewater is of interest for small and dispersed olive mills enterprises, which cannot afford large, complex and O&M intensive wastewater treatment facilities (Kapellakis et al., 2006). Centralized management minimizes or diminishes the environmental impacts at the production site, since the wastewater is transported in a different location where it is appropriately treated (Fig. 1). Demoted land such as abandoned sites, historically polluted areas, (closed) landfills and dumping sites are excellent applicants for sitting a centralized OMW facility.

The proposed centralized OMW facility (Fig. 2) consists of a storage lagoon, where the wastewater generated during the campaign, is transported and disposed of. The wastewater inside the lagoon is subject to sedimentation and acidification. The lagoon is isolated at the bottom using a synthetic liner, to avoid wastewater percolation into the ground water, while a floating cover can also be installed to control odors and insects and decrease evaporation,

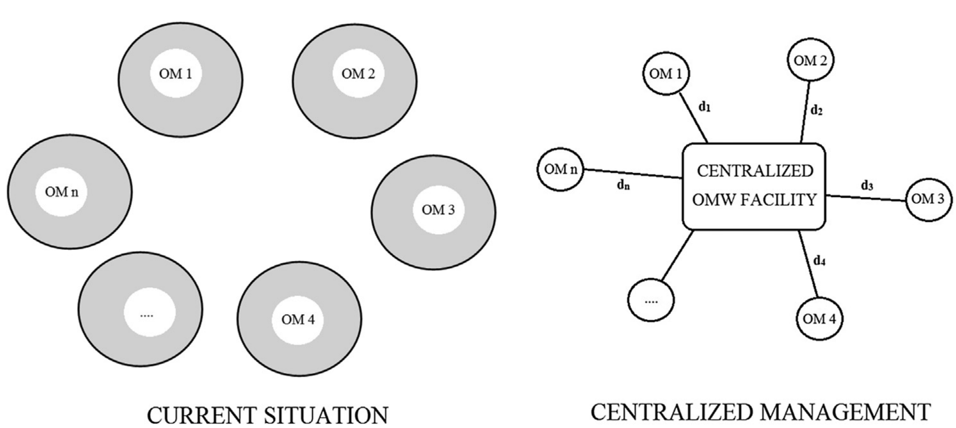

Fig. 1. System analysis of (a) small and dispersed olive mills (OM1, OM2, …n) and the environment affected by current OMW management practises (E1, E2, …n), and (b) the proposed solution of wastewater transport to a centralized facility ($d_{i..n}$ = distance of individual olive mill enterprise from the centralized facility).

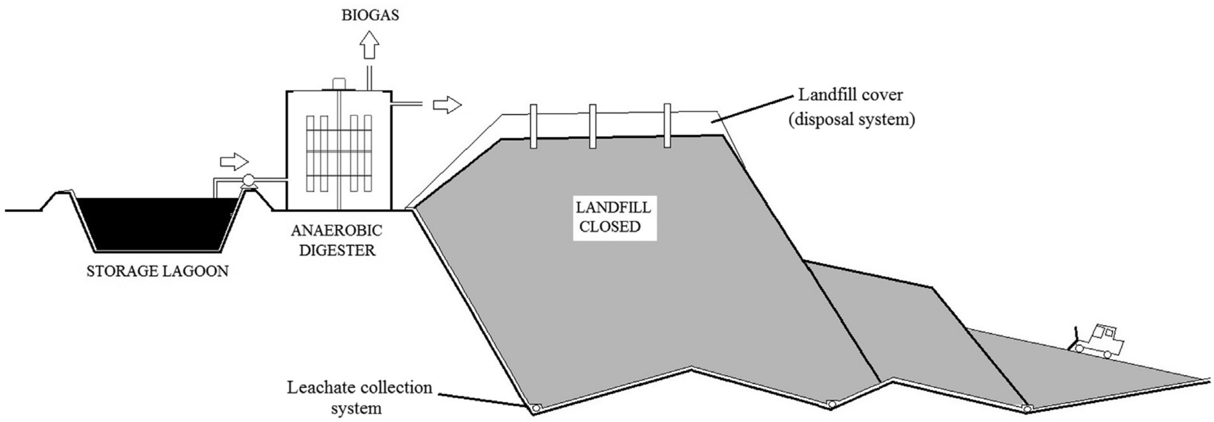

Fig. 2. Schematic representation of a centralized olive mill wastewater facility constructed in the vicinity of an operating or closed landfill site.

during the dry period of the year. This is important since landfill sites might be breeding grounds for mosquitoes, insects and other disease-causing vectors (Al-Yaquot, 2003).

The wastewater from the storage lagoon is fed to a compact anaerobic digester that is operated all year round. The digester is preferably a continuous stirred tank reactor (CSTR) with biomass recycle (contact process) operated under mesophilic conditions. In case of low wastewater suspended solids, an upflow anaerobic sludge bed (UASB) digester or a combination of both (CSTR and UASB) can be used. Before being fed to the anaerobic digester, the OMW is diluted with water to the desired COD concentrations (See Section 5.3). The dilution water is obtained from the groundwater monitoring wells of the landfill-site. The anaerobic effluent is disposed (pumped) into the landfill soils or the waste body, either alone or together with landfill leachate recirculation (see Section 5.5).

3. Effect of wastewater disposal to landfills

During wastewater disposal, percolation into the waste body is achieved and the quantity and the characteristics of the leachate produced will be affected. This depends on several factors, such as the characteristics of the refuse/waste, nature/strength of the wastewater type, operation protocol (organic loading rate, leachate recirculation), landfill age as well as physical, chemical and microbial processes altering wastewater composition during infiltration through the landfill body (Rahim and Watson-Craik, 1997; Percival and Senior, 1998; Tatsi and Zouboulis, 2002). It has been reported that if co-disposal is effectively controlled, the leachate produced should not differ greatly from the landfill leachate (Percival and Senior, 1998). In order not to affect the leachate quality significantly during co-disposal, the loading rate of an industrial wastewater was defined as the maximum quantity that is disposed annually with 1 kg of domestic refuse (Senior et al., 1990). The loading rates between 0.17:1 and 0.016:1 reported by Sumner (1978) were based on the past practices, assuming that the whole volume of solid wastes at each site was active in absorbing liquids. Comprehensive guidelines, however, are currently missing.

Landfills and dumping sites have often been characterized by a diverse microbial community, capable to perform multiple tasks such as recalcitrant wastewater degradation (Barlaz et al., 1990; Staley et al., 2011). The microorganisms obtained from the refuse of landfills and laboratory reactors were indeed shown to anaerobically degrade benzene, toluene, ethylbenzene, xylenes, phenol and p-cresol (Wang and Barlaz, 1998). Moreover, by wastewater application it is possible to enrich the landfill-refuse with metabolically active microorganisms. Zhang et al. (2012) enriched ammonia-oxidizing bacteria (AOB) on the refuse by incubating it in livestock wastewater. The treated refuse was found be effective to further use as a bio-cover on the landfill sites, and improved the oxidation of methane gas diffusing out of the waste (Zhang et al., 2012).

To examine the effect of wastewater disposal on refuse stabilization and leachate quality, agro-industrial residues such as brewery wastewater (Rahim and Watson-Craik, 1997), olive vegetation water (Cossu et al., 1993) and livestock wastewater have been studied (Zhang et al., 2012). Cossu et al. (1993) reported increased gasification without any inhibition of refuse degradation, when olive vegetation water was used. Rahim and Watson-Craik (1997) demonstrated that the disposal of a synthetic wastewater having a COD concentration of 1100 mg/L (95 mg/L acetate, 120 mg/L propionate, 60 mg/L formic acid, 100 mg/L glucose, 225 mg/L lactate, 500 mg/L ethanol) in refuse columns, stimulated methane production and did not affect the leachate quality. The authors used landfill columns with length = 50 cm and internal diameter = 5.5 cm (total volume = 1 L) and the applied loading rate was 1.05 cm/h and 2.32 cm/h, respectively. However, increasing the wastewater strength led to the accumulation of organic acids and decrease of the leachate quality, indicating the importance of wastewater pre-treatment before landfill application.

In another study Watson-Craik and Senior (1990) studied the effect of phenol wastewater (initial concentration 188 mg/L) disposal on landfill columns. The experiments were conducted in batch mode with continuous wastewater recirculation through the column. Different columns were used with varying hydraulic loading rates of 2.4, 1.6, 0.9, 0.5 and 0.3 cm/h. This study showed that phenol was efficiently degraded under all operating conditions and that increasing the loading rate maximized phenol attenuation.

Leachate recirculation was reported to improve the landfill leachate quality (Percival and Senior, 1998; Agdag and Sponza, 2005). High-strength phenolic wastewater (500–1000 mg/L phenol) together with thickened/dewatered waste activated sludge was co-disposed with refuse. Leachate recirculation at 1.1 cm/h increased the phenol degradation to 70–80%, which was attributed to the selection of the phenol-catabolizing microbial population in line with the increased retention time. On the other hand, batch-mode operation and single elution negatively affected the fermentation rate (10–20% removal) and in turn the leachate quality. Therefore, even if the inhibitory wastewaters are co-disposed and treated by means of the landfill, the wastewater characteristics (composition, concentrations) and operational conditions are important variables for efficient wastewater degradation in the landfill.

Similar results on anaerobic digestion and leachate characteristics were also obtained for a co-disposal study with dye industry sludge and the organic fraction of municipal solid wastes (OFMSW) (Agdag and Sponza, 2005). COD and VFA removals were improved as a result of the industrial sludge co-disposal, leading to a leachate COD concentration of 4200–5700 mg/L compared to 7100 mg/L from the control column (OFMSW) and VFA concentration of 600–1300 mg/L compared to 1600 mg/L from the control column. Recirculation of the leachate (at 3.8 cm/d) was speculated to improve the acclimation and detoxification due to the dilution of the potentially toxic substances in the dye sludge.

4. Uncontrolled wastewater disposal to landfills

Industrial wastewater application to landfills was an established co-disposal practice in the UK (Sumner, 1978; Senior et al., 1990). Continuous and uncontrolled disposal in non engineered (landfill) facilities was performed since 40–50s in the UK and more recently in Kuwait (Al-Yaqout and Hamoda, 2002). Yet, when the design and the operation of the site is not properly managed, the co-disposal might lead to the decreased stabilization rate and in turn the decreased leachate quality as formerly demonstrated at several co-disposal sites (Sumner, 1978).

At the "Pitsea" landfill site in South Essex (UK) a wide variety of liquid and solid industrial wastes were deposited for long time periods (Knox, 1983). Pitsea site covered 250 ha. It was used for domestic refuse disposal since 1920's. Liquid wastes were discharged into a series of trenches dug in areas of partially decomposed refuse. As reported by Knox (1983), this site was a major disposal outlet for industrial wastes in the UK, and especially 130,000 tn/yr industrial wastes, 110,000 tn/yr liquid wastes, 300,000 tn/yr domestic refuse, and up to 260,000 m^3/yr rainfall. The leachate generated was recycled in disposal lagoons dug on to the landfill. Leachate was characterized by a pH = 8.0–8.5, COD = 850–1350 mg/L, BOD = 20–250 mg/L, ammonia nitrogen = 200–600 mg/L and TSS = 100–200 mg/L, indicating no significant inhibition of refuse degradation with industrial waste components. Analyses of different hazardous constituents in leachate samples (heavy metals, cyanides, PCBs, pesticides, etc) showed that the co-disposal did not contribute to an increase in the concentration of hazardous compounds.

Al-Yaqout (2003) presented a comprehensive study about waste management practices in Kuwait. Disposal of industrial liquid wastes in non-engineered landfills (dumping sites) is a common practice there. Five dumping sites were studied concerning the amount and the characteristics of the industrial wastewater added. The wastewater had high concentrations of COD (up to 70,000 mg/L), BOD (up to 5000 mg/L), suspended solids (up to 14,000 mg/L) and heavy metals. They originated from slaughterhouses, dairy factories, food factories, soft drink industries and other industrial sources. Almost 2 million tn per year of liquid wastes were disposed of in Kuwait dumping sites. However the method of application and the loading rates were not provided and the only reference given was that the liquid wastes were continuously dumped in most sites either mixed with the solid waste or separately (Al-Yaqout and Hamoda, 2003). The quality of leachate was not affected and was typical of dumping sites without wastewater co-disposal (Al-Yaqout and Hamoda, 2003).

5. Case study

The Eastern part of Samos Island (Greece) is home of eight (8) olive mill enterprises as shown in Figure S1 (Electronic Supplementary Material). The Landfill site is situated on the Northern part of the island near the capital city (Vathy). The wastewater production (annual and daily), the campaign duration and the distance from the landfill-site of different olive oil enterprises of Eastern Samos Island are given in Table 1.

5.1. Wastewater transport

Wastewater transport is preferably accomplished by tank truck. The capacity of the tank is selected based on the average daily production of OMW from each olive mill. During a working day, the truck is loaded with OMW and transports it from each factory to the centralized facility. Based on the distance of each olive mill enterprise from the landfill site (d_i), the total distance traveled by the truck daily is:

$$D_t = 2\sum_{i=1}^{n} di,$$

where

D_t = the total traveled distance (km)
d_i = the distance of each olive mill enterprise from the landfill (km)
n = the number of olive mill enterprises

The total time required for transport, loading and unloading is:

$$T = 1.25^*\left[\frac{D_t}{V} + n^*(T_L + T_E)\right],$$

where

T = total time (h)
V = average truck speed (km/h) (20–50 km/h based on local roadway conditions)
n = number of olive mill enterprises
T_L = time required for loading the truck (h)
T_E = time required for unloading the truck (h)
1.25 = safety factor for unpredicted delays (traffic jam, etc)

In the case study of East Samos Island, a tank truck having a capacity of 13 m^3 was selected for wastewater transport, based on the average daily OMW production. During a working day, the total distance traveled is 2 × 101 = 202 km. Assuming an average truck speed (40 km/h) and the time required for loading and evacuating the truck (20 min each), the working hours were calculated as 14 h per day. Therefore, two trucks were required to complete the task

Table 1
Wastewater production, campaign duration and distance from the landfill-site of different olive mill enterprises of the Eastern Samos Island.

Olive mill enterprise	Campaign duration (d)	Wastewater production per campaign (m^3)	Average daily wastewater production rate during campaign (m^3/d)	Distance from landfill (km)
1	88	1500	17	14
2	150	1000	7	14
3	94	1080	12	13
4	66	1080	16	5
5	78	1020	13	14
6	90	1020	11	5
7	80	1000	13	18
8	82	1020	12	18
Total		8720 m^3/yr	101 m^3/d	101 km
Average	90 (±25)	1090 (±170)	13 (±3)	13 (±5)

Numbers in parenthesis for standard deviation.

on a 7 hour-shift basis. The purchase costs for two second-hand tank trucks of 13 m^3 were approximately 50,000 €. Considering a 15 years life-time and 6% interest, the annual capital expenditures (CAPEX) was 5150 €/yr, which corresponds to 0.59 €/m^3 of OMW transported. The annual CAPEX was calculated based on the following equation:

$$R = \frac{P}{\frac{(1+i)^n - 1}{i(1+i)^n}},$$

where

R = annual equivalent cost (€)
P = present value or worth (€)
i = interest rate
n = number of years

The operational expenses (OPEX) include diesel consumption and the labor. Average diesel consumption by the truck was assumed 40 L/100 km which corresponds to 120 €/day (considering a diesel price of 1.5 €/L). During the annual campaign (maximum 4 months) the total costs for diesel were therefore equal to 14,400 €. The driver-wages are 2*(4 months)*(2000 €/month) = 16,000 €. Based on the quantity of wastewater transported per season, the OPEX was 3.49 €/m^3. Therefore, the total cost for wastewater transport was ~4.08 €/m^3.

5.2. Storage lagoon

The wastewater storage lagoon is constructed according to the maximum wastewater quantity generated during the campaign season. The local water balance (rainfall, evaporation) should also be considered in case of open storage lagoons. The sediment collected from the lagoon is used as a soil conditioner or as a landfill cover.

The lagoon is generally designed as a typical anaerobic pond having a depth of 2.5–4.5 m (EPA, 2011). It is covered during the summer with a floating cover, to decrease evaporation and control odors and insects. The construction costs are in the order of 11 €/m^2 (EPA, 2011), and include HDPE liner and cover, site preparation (excavations, grader, roller compactor, JCB digger), staff-wages, engineering and supervision. A free board of 0.5–1.0 m should also be included in the calculations.

For the eight (8) olive mills under consideration, generating a total of 8700 m^3 of wastewater per year (minus 2160 m^3 or 24 m^3/d of OMW abstracted for anaerobic digestion during the campaign), a lagoon of 3500 m^2 with 2.5 m depth, suffices and the capital costs are equal to (3500 m^2)*(11 €/m^2) = 38,500 €. The design includes a free board of 0.5 m. Considering a 15 years life-time and 6% interest, the annual CAPEX is 3970 €/yr, which corresponds to 0.46 €/m^3 of OMW wastewater.

5.3. Anaerobic digester

OMW pre-treatment is a pre-requisite before disposal to landfill sites, in order to control diffuse methane emissions. Organic-rich effluents, such as those generated from agro-industrial facilities, will eventually enhance biogas production from the landfill (Cossu et al., 1993). However, the quantity of biogas (methane) recovered is not higher than 50% of the theoretically expected (Lombardi et al., 2006; Themelis and Ulloa, 2007). This is mainly due to diffuse methane losses which are considered unsustainable in terms of the carbon footprint (Fruergaard et al., 2009).

High-rate anaerobic digestion is a promising technology for OMW pre-treatment (Raposo et al., 2004; Koutrouli et al., 2009). The process enables organic matter degradation, without energy intensive aeration, and biogas production (rich in methane), which can be used for electricity and/or heat production.

An anaerobic digester operated with diluted two-phase olive mill pomace (COD = 21.5 g/L) displayed high process stability at an Organic Loading Rate (OLR) = 3–4 kg/(m^3d) and Hydraulic Retention Time (HRT) = 7–10 d (Raposo et al., 2004). Indeed, COD removal efficiency was between 80 and 85% and a final effluent COD = 4 g/L was achieved (Raposo et al., 2004). By decreasing the influent COD concentration to 16 g/L, COD removal efficiency was not significantly improved (83%) but process stability was guaranteed at low HRT (=3 d) and relatively high OLR [=5 kg/(m^3d)] (Ammary, 2005). This is important concerning digester design optimization.

On the contrary, by increasing the OMW COD concentration to 47–79 g/L, process instabilities were encountered, especially when the OLR was higher than 3 kg/(m^3d) and the HRT was lower than 15–20 d (Martin et al., 1994; Borja et al., 1995; Blika et al., 2009). Therefore, high-rate anaerobic digestion of OMW is possible after OMW dilution to COD 10–20 g/L (Azbar et al., 2004). Stable digester performance is also possible at high OLR [up to 7 kg/(m^3d)] if pre-acidification is included (Blika et al., 2009). Under these conditions, methane yields in the order of 0.30 m^3/kg COD removed (Raposo et al., 2004), volumetric biogas production rates up to 1.7 m^3/(m^3d) and the methane contents around 65% are feasible (Blika et al., 2009).

The digester is designed according to the wastewater composition (COD, SS, degree of acidification) and the flowrate (sum of OMW and dilution water) (Lettinga and Hulshoff-Pol, 1991). The dilution factor depends on wastewater COD inside the storage lagoon and therefore actual measurements are required. Taking as an example the annual production of 8700 m^3 of OMW, the daily OMW flowrate to the digester is 8700/365 = 24 m^3/d. For a COD concentration inside the lagoon of 50 g/L (Gikas et al., 2012), a dilution factor of 3 is required, giving a total influent flowrate to the digester 70 m^3/d. The latter is designed at an OLR = 4 kg/(m^3d) and the operational volume is = (24 m^3/d)*(50 kg/m^3)/[4 kg/(m^3d)] = 300 m^3.

The capital costs (CAPEX) for a 300 m^3 digester are in the order of (300 m^3)*(1000 €/m^3) = 300,000 € (Personal communication with wastewater contractor, Greece). The latter include the reactor tank (concrete with thermal insulation), wastewater distribution system and pumping station, solids separator and recycling, pipes, valves, biogas handling equipment, gas boiler and heat exchanger, gas holder and CHP, process monitoring equipment, engineering and supervision. Considering a 15 years life-time and 6% interest, the annual CAPEX is 30,900 €/yr, which corresponds to 3.55 €/m^3 of OMW wastewater treated.

Digester operation requires wastewater feeding and sludge recycling pumps (total 2.5 kW) and a slow mixer (max 0.5 kW). Therefore, annual electricity consumption is (3 kW)*(20 h/d)*(365 d) = 21,900 kWh which corresponds to 2600 €/yr or 0.30 €/m^3 OMW at 0.12 €/kWh. Digester heating is performed with the generated biogas or the landfill gas itself. Labor is not included in the calculations since supervision is possible by the operator of the landfill and the leachate treatment plant.

5.4. Energy recovery

The methane gas generated by the digester, was estimated according to the daily COD load, the COD removal efficiency (85%) and the methane yield (0.30 m^3/kg CODremoved) (Raposo et al., 2004; Ammary, 2005; Martin et al., 1994; Borja et al., 1995; Blika et al., 2009). Therefore, (24 m^3/d)*(50 kg/m^3)*(0.85)*(0.30 m^3/kg) = 300 m^3/d of methane were recovered, which corresponds to (300 m^3)*(3 kWh_{el}/m^3) = 900 kWh_{el} per day.

Table 2
Capital (CAPEX) and operational expenses (OPEX) of a centralized OMW facility treating 8700 m^3 OMW wastewater per year.

Cost	Total	Annual	Per m^3 wastewater
CAPEX			
Lagoon	38,500	3970 €/yr[a]	0.46 €/m^3
Digester	300,000	30,900 €/yr[a]	3.55 €/m^3
OPEX			
Electricity		2600 €/yr	0.30 €/m^3
Total			4.31 €/m^3

[a] 15 years life-time and 6% interest.

Electricity introduction to the grid (at 0.22 €/kWh) can therefore provide an income of ~72,000 €/yr, or 8.31 €/m^3.

Table 2 provides an overview of the capital and operational expenses of the proposed OMW centralized facility. It is therefore evident that the facility is self-sufficient in economic terms, as long as the transportation costs of the OMW are maintained at ≤4.0 €/m^3.

5.5. Final wastewater disposal

Landfill disposal of the pre-treated wastewater is possible in practice through the existing leachate recirculation system. In this case, the costs for disposal are negligible, since the anaerobic effluent is simply fed into the leachate collection or recirculation tank. For recirculation landfills, however, this addition should take into account the water balance and hydraulic capacity of the leachate treatment plant, in order to avoid overloading, when large quantities of wastewater are considered. In Table 3 different technologies for wastewater disposal are reviewed concerning design parameters, advantages, disadvantages and costs.

Wastewater application may be performed in a separate infiltration field installed on the top of the landfill soil cover. To this end, both trenches and infiltration lagoons or wells can be employed. Special care should be given by the design engineer to ensure uniform wastewater application and minimize short-circuits. Infiltration lagoons were installed for leachate recirculation in Nepean, Ontario, Canada (Warith, 2002). The location of them was constantly changed to ensure uniform distribution of the leachate into the waste. However, short-circuiting restricted the landfilled waste from reaching 100% of its field capacity. For a horizontal trenches distribution system, detailed design guidelines were given by Reinhart et al. (2002), although actual measurements of soil cover and waste hydraulic conductivity are necessary. According to Reinhart et al. (2002) the design hydraulic loading rate, based on waste hydraulic conductivity, is 10^{-4} cm/s or 0.36 cm/h. This value was used for a preliminary design of the final wastewater disposal system for our case study. Details about trench design are presented in Table 3, while the detailed calculations are given in Electronic Supplementary material.

Another option to design the disposal field is to enhance wastewater evaporation. This is possible under Mediterranean climatic conditions where net annual evaporation is significant, ranging from 400 to 1200 mm/yr (Mariotti et al., 2002). An evaporation disposal system based on trenches was preliminary designed for our case study (see Electronic Supplementary material) considering a net annual evaporation of 800 mm and a respective hydraulic loading of 0.8 $m^3/(m^2\ yr)$. Under these conditions, a significant part of the wastewater may be evaporated during the dry period of the year, while the disposal surface area

Table 3
Design parameters, costs and evaluation of potential wastewater landfill disposal systems.

Technology	Design parameters	Cost[a] €/m^3	Advantages	Disadvantages
Infiltration systems				
Trenches	Surface loading rate = 0.36 cm/h (waste conductivity) Trench loading rate = 2–4 m^3/(m d) Trenches spacing = 5–12 m Feeding = periodic, 8 h feeding, 16 h relaxation Pipe type = flexible, high density, slotted Trench filling materials = gravel, tire chips, etc	0.21	• Easy to construct • Good moisture distribution • Efficient control of wastewater flowrate • Minimum drilling into the waste mass	• Large area required • Difficult maintenance and inspection • Slot and filling material clogging (biofouling, suspended solids) • For gravity systems: • Frequent inspection and control. • Possible repositioning of trenches (due to waste settlement)
Wells	Well loading rate = 5–10 m^3/d per well Well diameter = 50–150 cm Well depth = 1.0–2.0 m Influence radius = 4–7 m	0.27	• Easy maintenance and inspection • Easy to construct (drilling into the waste mass)	• Preferential flow • Large number of wells required (for uniform distribution)
Evaporation systems				
Natural evaporation	Similar to trenches construction (excavations and pipes) Surface loading rate based on net annual evaporation	0.26	• Enhanced wastewater losses (due to evaporation) • Minimum impact on landfill • Control of wastewater infiltration	• Large area required • Wastewater storage is required (during heavy rain periods)
Wetland evaporation	Similar design to constructed wetlands Surface loading rate according to net annual evaporation Wastewater distribution pipes directly onto the landfill cover Uniform application of gravel material on the landfill cover Plantation with hydrophilic vegetation (reeds, phragmites)	0.31	• Additional wastewater purification • Maximum evapo(transpi)ration • Potential purification of landfill gases	• Increased construction costs

[a] CAPEX + OPEX per m^3 of wastewater disposed (this includes dilution water applied before anaerobic digestion).

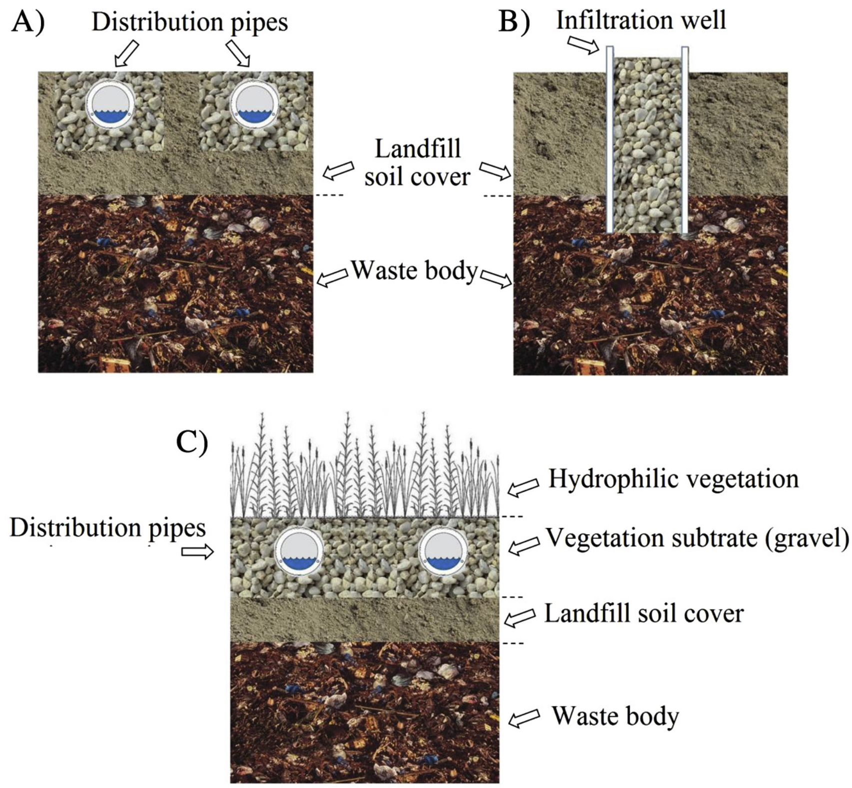

Fig. 3. Schematic representation of potential wastewater landfill disposal systems: A) trenches, B) infiltration wells, and C) enhanced hydrophilic evaporation.

required was twice as large compared to the previous (infiltration) technology. Accordingly, the costs were higher by a factor of 25% and reached 0.26 €/m^3 wastewater disposed (see Table 3). Water evaporation can be further enhanced by fostering hydrophilic vegetation onto the soil cover (Nyhan et al., 1990; Albright et al., 2004). In this case a significant cost factor included the purchase and placement of substrate (gravel) and plants. A schematic representation of different wastewater disposal systems is given in Fig. 3. The detailed calculations used for system design and costing are given in Electronic Supplementary material.

6. Conclusions

- Demoted areas such as landfill sites are proposed to be valorized for controlled olive mill wastewater (OMW) disposal. Although currently this practice is not permitted by the European legislation, it is considered as an environmentally and economically sustainable solution for OMW management for small islands and decentralized areas.
- OMW pre-treatment is a prerequisite before disposal to the landfill, in order to minimize its impact on leachate quality.
- Pre-treated OMW disposal to landfill can contribute to enhanced waste degradation and increased landfill gas production, due to moisture increase inside the refuse mass.
- For OMW management, a landfill-based centralized facility is justified in economic terms. The latter consists of a wastewater storage lagoon and a compact anaerobic digester operated all year round. The biogas generated from the digester is used for electricity production, thus an income is provided which compensates for the costs of wastewater transport.
- Small and dispersed olive-mill enterprises can benefit, since wastewater treatment facilities are not required on-site.
- Future research should focus on appropriate OMW pretreatment technologies, the effect of pre-treated OMW characteristics (COD, BOD, phenols) on landfill processes, the permissible hydraulic and organic surface loading rate, and the type of wastewater disposal system. Field studies are necessary to obtain reliable design data for wastewater application.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2013.05.051.

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