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ORIGINAL PAPER

Adding Value to Olive Oil Production Through Waste and Wastewater Treatment and Valorisation: The Case of Greece

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Abstract Nowadays, an increasing trend towards olive oil production is observed globally. The extraction of olive oil is mostly implemented through three-phase or two-phase centrifuge systems. Olive pomace, derived as a by-product of olive oil processing, constitutes a raw material for olive–pomace oil production. The operation of olive oil mills and olive–pomace industries has been connected with the generation of heavily polluted wastewater and solid waste. The present paper aims at investigating the current treatment methods and techniques applied for the management of the wastewater and solid waste generated by olive oil (including olive–pomace oil) production in Greece. Aiming at adding value to the Greek olive production process, international practices applied for solid waste and wastewater treatment as well as potential valorisation options are reviewed within this paper. The results reveal that there is room for improvement in wastewater treatment in Greece, since the currently applied method, i.e. oil removal, neutralisation, sedimentation and evaporation in open lagoons, comprises only a basic—level treatment technique. Concerning solid waste management, attention must be paid to the use of sludge produced from the evaporation ponds, since its application as soil improver without appropriate treatment may entail diverse toxic effects to soils. Regarding solid waste valorisation, pomace handling is thoroughly exploited in Greece, since it is utilised for the production of olive–pomace oil and pomace wood. Other valorisation opportunities, identified in the literature, include production of biomolecules as well as cosmetic products, dyes, construction materials and water decontamination sorbents. However, more work is needed in order to maximise the economic feasibility and applicability of such practices.

Keywords Olive oil · Olive pomace oil · Pomace wood · Pomace · Centrifuge · Waste · Wastewater · Greece

Introduction

Globally, olive oil production is characterised by a continuous upward trend that peaked during the last decade, reaching 3.3 million tons for the 2011/2012 olive crop year [1]. In 2011/2012, approximately 72 % of the world's production came from European countries, 96 % of which was produced from three countries: Spain (49 %), Italy (12 %) and Greece (9 %) [1]. During the last decade, Spain has greatly intensified the cultivation of olive trees, achieving a rapid increase of oil production to approximately 1.3 million tons in 2010, thus doubling their production since 1990 [2]. The raw material used for the production of *olive oil* is olives, while *olive–pomace oil* is produced from a by-product derived of olive production process known as pomace. Olive oil is the main fatty component of the Mediterranean diet [3], while olive–pomace oil can be used for: soap manufacturing, dietary purposes (after refining and mixing with olive oil), biodiesel production and cosmetics.

Overall, Greece has an annual production ranging from 300 up to 400 thousands of tons of oil depending on the olive crop year [4]. During the period 2007–2009, approximately 300 thousands of tons were produced, 75 % of

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which were produced in Crete and Peloponnese [2]. In general, the olive oil sector includes olive oil mills (OOMs), olive–pomace oil production facilities, packaging facilities as well as refinement facilities. OOMs can be categorised, according to the quantity of olives processed in a 2 year period (sum of maximum and minimum year production) to three basic categories: (1) small sized companies where the processing capacity is less than 1500 t olives/2 year period (2) medium sized companies where the processing capacity is between 1500 and 3000 t olives in a 2-year period and (3) large sized companies where the processing capacity is greater than 3000 t olives in a 2-year period [5]. In 2009, 2369 OOMs were recorded in Greece, 37 % of which operated in Peloponnese and 23 % in Crete [2]. Furthermore, according to 2011 data, 260 approved packaging facilities were identified without including the small capacity units operating without a proper license [2]. Finally, 47 companies operating in Greece produce olive–pomace oil (2012 data) [2]. These facilities are annually supplied with around 200 thousands of tons of pomace [2].

In general, the olive oil production process is accomplished through a sequence of activities including: reception of olives, cleaning of impurities, washing with water, crushing of olives, malaxation of paste, olive oil extraction, final centrifugation, storage, filtration and bottling [3]. The basic process is the olive oil extraction which was traditionally carried out through pressing. Nowadays, the extraction in most OOMs is performed with the centrifugal process through three-phase or two-phase decanters. Three-phase decanters were the first applied centrifugal systems for olive oil extraction, resulting in the production of three streams i.e. (1) olive oil mixed with water for further centrifugation, (2) wastewater (known as *vegetable or fruit water* in English, *alpechin* in Spanish, *acque di vegetazione* in Italian and *katsigaros* in Greek) and (3) solid waste (known as *pomace* in English, *orujo* in Spanish, *sansa vergine* in Italian and *trifasikos elaiopirinas* in Greek). The two-phase decanters turned up later as a more environmental friendly method for olive oil centrifugation. Two-phase decanters produce two streams i.e. (1) olive oil for further centrifugation and (2) solid waste (known as *pomace* in English, *alperujo* in Spanish, *sansa vergine* in Italian and *difasikos elaiopirinas* in Greek). Pomace produced from 2-phase systems is characterised by higher humidity ($\sim$62 %) compared to that from 3-phase systems ($\sim$55 %). Pomace from both 3-phase and 2-phase systems is transported to olive–pomace oil facilities. Pomace oil plants process the pomace produced from the two or three phase OOMs for the production of olive–pomace oil. In summary, the method includes: reception and storage of fresh pomace, drying of pomace, extraction of dry pomace, distillation, concentration of hexane-water, separation of hexane-water and storage of olive–pomace oil. In addition to the oil produced, exhausted pomace or pomace wood (*orujillo* in Spanish, *sansa esausta* in Italian and *pirinoxilo* in Greek) is also produced.

The main target of this research is the recording and evaluation of the current practices applied for the treatment of the wastewater and solid waste derived from the olive oil processing industry in Greece in order to uncover opportunities for adding value to the olive oil process through alternative waste and wastewater treatment practices and potential valorisation of derived waste streams. To this end, the existing solid waste and wastewater management status in Greece as well as the worldwide practices and exploitation opportunities were studied. Mapping of data concerning treatment methods applied in Greece were collected based on a methodology specifically developed for the needs of this study. Following, the methodology developed and the results obtained are discussed.

Methodology

The research was carried out following two directions: (a) the recording of the existing management of waste and wastewater generated during olive oil processing in Greece and (b) the reviewing and recording of waste and wastewater treatment methods and valorisation options proposed by research publications and presentations worldwide.

In order to assess the currently implemented practices in Greece, a four-step methodology was developed and adopted, as illustrated in Fig. 1.

During the *first step* of the methodology, an extensive desk research for the collection of secondary data related to Greek companies involved in the olive/pomace-oil production and packaging was carried out. This information was collected through companies' websites created to promote their products or websites related to olive oil production at national level, such as the Hellenic Ministry of Rural Development and Food, regional chambers of commerce and industry, published online catalogues of related industries, etc. In the first research step, information regarding the name of the industry, the location, contact details, revenues and the specific industrial activity to which it belongs, were gathered and recorded. The industries were categorised based on their activity as related to: Olive Oil Production (OO-PR), Olive Oil Packaging (OO-PA), Olive–Pomace Oil Production (OPO-PR), Olive–Pomace Oil Packaging (OPO-PA) and Soap Production (SP). The *second step* aimed at the collection of information on the current situation related to the generation and treatment of wastewater and solid waste from the production process of the oil industries recorded in the framework of the *first step*. The above mentioned data were collected through

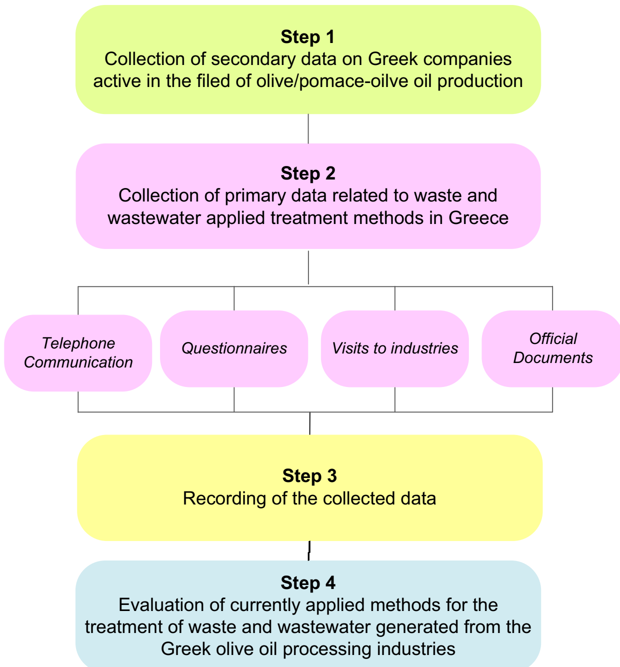

Fig. 1 Methodology for recording management methods for treating wastewater and waste from olive oil production in Greece

telephone contacts, questionnaires, visits to industries and finally through available official information (i.e. Approval of Environmental Impact Assessment) from the Greek Ministry of Environment, Energy and Climate Change (YPEKA). The *third step* involved the recording and grouping of the primary data collected during the implementation of the second step, in order to facilitate the evaluation. More specifically, the following data were recorded: categorisation in group/subgroup/category, capacity, type of oil extraction, information on wastewater generated from the production process (type and quantity, management methods, valorisation/disposal) and information on solid waste generated during production process (type and quantity, management methods, valorisation/disposal). Categorisation in group, subgroup and environmental category was elaborated based on the Ministerial Decision (MD) 1958/12 *on the classification of projects and activities into categories/subcategories on the basis of their potential impact on the environment* (Government Gazette B/21/2012) [6]. The *fourth step* involved the interpretation and evaluation of the collected information so as to depict the current status of wastewater and waste treatment from olive oil production in Greece. Activities related to the sector under investigation belong either to *Category A2* or to *Category B*. Category A2 activities may cause significant adverse environmental impacts and, thus, the conduction of an Environmental Impact Assessment (EIA) is obligatory. In such activities (A2), the approval of the Environmental Impact Assessment is issued from the regional environmental authority. Category B includes activities that can only cause local and non-significant effects on the environment and, thus, are only subject to Standard Environmental Commitments (SEC).

In order to uncover potential opportunities for adding value to the olive oil process through waste and wastewater treatment and valorisation, review of the waste and wastewater treatment methods and valorisation options applied worldwide was also conducted.

Results and Discussion

In total, 274 companies related to olive/olive–pomace oil production and packaging were identified during the first step of the methodology, out of which around 64 % are OOMs and approximately three quarters of those (72 %) are also engaged in olive oil packaging. Moreover, 3 % of all enterprises produce olive–pomace oil out of which about 14 % are also packaging olive–pomace oil. Finally, 33 % is dedicated to packaging of oils, out of which 96 % is engaged to packaging of olive oil. Most of the recorded companies operate in Peloponnese (39 %), in Crete (22 %) and in Western Greece (21 %).

From the implementation of the second step of the methodology, data for 22 Greek industries related to oil production and packaging were collected through the methods discussed in the methodology section. Among those, 16 are involved in oil production (olive oil mills), nine out of which have extended their activities to the packaging of olive oil. Among the remaining industries, two were exclusively active in the packaging of olive oil and four in the production of olive–pomace oil and pomace wood, three out of which are also engaged in the packaging of olive–pomace oil, while one of them also produces soaps.

According to the MD 1958/12, industrial activities are classified under the 9th group of Annex IX ("*Industrial Activities and Related Facilities*") with serial numbers depending on the activity i.e. (a) No. 11 corresponds to *olive oil production*, (b) No. 12 matches with the *production of refined oils and fats and of margarine and similar edible fat*, (c) No. 13 is related to the *manufacture of other non-processed oils and fats* and (d) No. 14 is relative to *drying of oil seeds, other agricultural products and plant biomass*. Approximately half of the industrial units studied belong to category A2 which is either related to the productive capacity and/or other special issues, such as the location of the units, etc. Data collected for the generation and management of waste from the industrial production and processing of oil industries in Greece are presented in Table 1.

Table 1 Recorded and categorised data for solid waste and wastewater treatment in 22 olive and olive–pomace oil industries in Greece

No.	Activity	Capacity	Industrial wastewater type and quantity	Industrial wastewater treatment and disposal	Sludge treatment and disposal	Industrial solid waste type and treatment method applied
1	OO-PR 2-phase	Olive oil mill: 9 t olives/day	0.25 m^3/t olive (3 m^3/day)	Neutralisation of acidity Flocculation Precipitation Transportation to the municipal wastewater treatment plant	n.a.	Pomace: to olive–pomace oil production facilities Olive leaves: for animal feed
2	OO-PR 3-phase	n.a.	n.a.	Neutralisation of acidity Flocculation Precipitation Surface water receptor	Sludge (precipitation tanks): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel Ash: disposal with MSW or for fertilising
3	OO-PR 3-phase	n.a.	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel Ash: disposal with MSW or for fertilising Damaged olives: animal feed or soil improver or for biogas production
4	OO-PR 3-phase	n.a.	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel Ash: disposal with MSW or for fertilising Damaged olives: for animal feed or soil improver or for biogas production
5	OO-PR 3-phase	Olive oil mill: 15 t olives/day Olive oil production: 3 t olive oil/day	n.a.	Screening Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, mixing with olive leaves, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: soil improver
6	OO-PR 3-phase	Olive oil mill: 20 t olives/day Olive oil production: 5 t/day	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel
7	OO-PR and other oils	Vegetable oils: 192 t of processed oil/day	25–30 m^3/day	Pre-treatment Physicochemical treatment Biological treatment Surface water receptor	Sludges: T&D: by appropriate waste treatment companies	Gums, waxes and solid waste from the refining process: added to flour or sold to third parties as a by-product for use Sediment material (mourga): sold to third parties for use (soap)

Table 1 continued

No.	Activity	Capacity	Industrial wastewater type and quantity	Industrial wastewater treatment and disposal	Sludge treatment and disposal	Industrial solid waste type and treatment method applied
8	OO-PR/ OO-PA 3-phase	50 t olives/day	1.2 t/t olives, 54 t/day	Neutralisation of acidity Flocculation Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: soil improver
9	OO-PR/ OO-PA 3-phase	Olive oil mill: 48 t olives/day Packaging: 320 t olive oil/day Oil refining: 120 t of unrefined oils/day	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel Ash: disposal with MSW or for fertilising Damaged olives: animal feed or soil improver or for biogas production
10	OO-PR/ OO-PA	n.a.	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel Ash: disposal with MSW or for fertilising Damaged olives: animal feed or soil improver or for biogas production
11	OO-PR/ OO-PA 2-phase	Olive oil mill: 24 t olives/day Packaging: 4.5 t olive oil/day	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel
12	OO-PR/ OO-PA 2-phase	Olive oil mill: 46.4 t olives/day Packaging: 4.8 t olive oil/day	0.15 t/t olives 6.4 t/day	Screening Neutralisation of acidity Precipitation Evaporation in ponds	n.a.	Pomace: to olive–pomace oil production facilities Olive leaves: soil improver
13	OO-PR/ OO-PA 2-phase	Olive oil mill: 2.4 t olives/day Packaging: 3.2 t olive oil/day	n.a.	Oil collection Septic and absorption tank	Sludge (septic tank): T—collection to the septic tank D—appropriate waste companies	Pomace: to olive–pomace oil production facilities Olive leaves: n.a. Sediment material (mourga): for soap production
14	OO-PR/ OO-PA 3-phase	Olive oil mill: 10 t olives/day	n.a.	Oil collection Neutralisation of acidity Precipitation Evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or as fuel (after drying) to the burner along with the pomace wood Ash: disposal with MSW or for fertilising

Table 1 continued

No.	Activity	Capacity	Industrial wastewater type and quantity	Industrial wastewater treatment and disposal	Sludge treatment and disposal	Industrial solid waste type and treatment method applied
15	OO-PR/ OO-PA 3-phase	Olive oil mill: 80 t olives/day Packaging: 10 t olive oil/d	From olive oil mill: 0.7 m^3/t olive, 53 m^3/day From washing of resins: 300 $m^3/year$	From washing of equipment and tanks: septic tank From decanter: Oil collection Neutralisation of acidity Precipitation Evaporation in ponds From washing of resins: appropriate companies	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Olive leaves: soil improver Resins: appropriate waste treatment companies Diatomaceous earth: appropriate waste treatment companies for composting
16	OO-PR/ OO-PA 3-phase	Olive oil mill: 28 t olives/day Packaging: <1 t olive oil/day	53 m^3/day	From washing of equipment and tanks: septic tank From decanter: Oil collection Neutralisation of acidity Precipitation Surface water receptor	Sludge (sedimentation tanks): T—collection D—soil improver	Pomace: to olive–pomace oil production facilities Olive leaves: animal feed or soil improver or fuel Dust from steam boiler: burning
17	OPO-PR	Pomace processing: 400 t pomace/day	n.a.	Industrial wastewater: septic tank & absorption system Leachates from pomace storage: collection and evaporation in ponds	Sludge (evaporation ponds): T—collection, dehydration, D—soil improver	Olive leaves: animal feed or soil improver or fuel Dust from steam boilers: burning with pomace wood Dust from dryers: extraction
18	OPO-PR/ OPO-PA	Processing: 400 t pomace/day Production: Olive–Pomace oil: 30 t/day Exhausted olive pomace 300 t/day	n.a.	Pre-treatment Physicochemical treatment Biological treatment Re-use to the biological treatment plant	Sludges: T&D: by appropriate waste treatment companies	Ash: disposal with MSW

Table 1 continued

No.	Activity	Capacity	Industrial wastewater type and quantity	Industrial wastewater treatment and disposal	Sludge treatment and disposal	Industrial solid waste type and treatment method applied
19	OPO-PR/ OPO-PA	Production of olive–pomace oil: 24 t/day	Wastewater from once-through water cooling system: 1600 m^3/day Concentrated vapours from the extraction process: 11 m^3/day Wastewater from neutralisation: 0.25 m^3/day From steam boilers: 1.20 m^3/day From washing of floors: 2 m^3/day	Wastewater from once-through water cooling system: for disposal surface water receptor Other industrial wastewater (concentrated vapours from the extraction process, wastewater from neutralisation, from steam boilers, from washing of floors): collection Disposal to municipal wastewater treatment plant	–	Ash: disposal with MSW or as fertiliser Dust from steam boiler and dryers: burning to dryer's or boiler's burner Paste of bleaching earth: disposal with MSW or as fertiliser Soap paste: treatment inside the facility for disintegration and production of oleins sold to various companies for use as biomass fuel in combination with fossil fuels or sold for soap production
20	OPO-PR/ OPO-PA/ SP(5)	Processing: 500 t pomace/day Production: Olive–Pomace oil: 10 t/day Exhausted olive pomace 110 t/day	Wastewater from once-through water cooling system, concentrated vapours from the extraction process, wastewater from neutralisation, from steam boilers, from washing of floors and equipment, leachates from pomace storage	Wastewater from cooling system, concentrated vapours from the extraction process, wastewater from neutralisation, from steam boilers: Reuse as cooling water and feed water to the steam boiler At the end of the operation period, disposal to evaporation ponds Leachates from pomace storage: collection and evaporation in ponds	Sludge (evaporation ponds): T—mixing with pomace and lead to dryers, D—n.a.	Ash: disposal with MSW or as fertiliser Dust from steam boilers: burning with pomace wood Dust from dryers: extraction Paste of bleaching earth and Diatomaceous earth: disposal with MSW or sold to other companies e.g. cement industries
21	OO-PA	Packaging: 40 t/day	n.a.	Collection	–	–
22	OO-PA and others	Packaging: 0.225 L/day	n.a.	Biological treatment plant	n.a.	n.a.

OO-PR, olive oil production; OO-PA, olive oil packaging; OPO-PR, olive–pomace oil production; OPO-PA, olive–pomace oil packaging; SP, soap production; n.a, not available information; –, not relative information; T, treatment; D, disposal

Based on the study conducted, the main products of the activities under investigation are: olive oil, refined oils, olive–pomace oil and pomace wood. Other intermediate products or by-products that are financially exploited directly or indirectly include: (a) pomace which comprises the raw material for olive–pomace oil production, (b) sediment material from oil storage tanks (in Greek: mourga) which is sold to soap manufacturing industries and (c) olive leaves which are forwarded as animal feed.

Regarding the production processes of the examined industries, the differences observed in the production of the same product were insignificant. Thus, the main stages for olive oil production include reception of olives, cleaning of impurities, washing with water, crushing of olives, malaxation of the paste produced from crushing, centrifugation (*3-phase or 2-phase decanters*), final centrifugation and storage. In this study, the majority of the studied OOMs (approximately 70 % from those that available data existed) were three-phase OOMs. Moreover, it was observed that the method of oil extraction determines both the capacity and the qualitative and quantitative characteristics of the resulting oil, wastewater and solid waste. For 3-phase OOMs, an average ratio of 0.23 kg of oil is produced/kg of olives processed.

The operation of OOMs results in wastewater and waste production. From a 3-phase process, besides oil mixed with water, wastewater and solid waste (pomace) are also generated, while from 2-phase decanters only olive oil mixed with water and pomace (with higher humidity than that pomace from 3-phase mills) are produced. The generated wastewater mainly comes from washing of olive oils, floor and equipment washing and the second centrifugation. Based on the recorded data and as it was expected, the average ratio of the generated wastewater (kg) per olives processed (kg) for the 3-phase system is much higher than that for the 2-phase system, 1.23 and 0.22 respectively. The vegetable water derived from the 3-phase decanters is responsible for the high polluting load and the black colour of the wastewater generated from OOMs using three-phase centrifugation. In Fig. 2, key information concerning the 3-phase and 2-phase OOMs studied are illustrated.

From the evaluation of the data it is obvious that the prevailing waste treatment method that is currently applied in Greece includes oil collection, neutralisation of acidity, sedimentation and disposal to open evaporation ponds (lagoons). Half of the industries studied use the evaporation ponds as the final treatment/disposal step. In general, the evaporation ponds are widely used despite the fact that in some cases only the waste volume is reduced and serious problems may occur due to the leakage of wastewater to soil and/or groundwater [9]. Despite that, the specific treatment method is a low cost method and thus widely applied [9]. It must also be noted that according to the Greek Joint Ministerial Decision (JMD) 15/4187/266/11.04.2012 on *the Standard Environmental Commitments (SEC) of Industrial Activities* (Government Gazette B 1275/B/11.4.2012) [7] and in particular condition E3 (Annex I), oil collection, neutralisation, sedimentation and final disposal to open evaporation ponds is the proposed treatment method for wastewater from olive oil production. Based on the same condition, an equivalent method can also be applied. Condition E3 has been further explained in the *Official Document (12550/744/F15/2.11.2012) on General guidelines for implementation of the condition E3 of JMD 15/4187/266/11.04.2012* issued by the General Secretariat for Industry and the General Secretariat for Environment [8]. Based on this document, neutralisation should be conducted with the addition of at least 5 kg of lime per ton of olives processed or at 2 % per unit volume of wastewater, while during precipitation the sediment should be left to settle for at least 3 h [8]. Moreover, three (3) companies are applying (approximately 14 % of the studied companies) oil collection, neutralisation of acidity, sedimentation and finally either disposal to a surface water receptor (2) or to a municipal wastewater treatment plant (1). Furthermore, two (2) industries apply a pre-treatment, followed by physicochemical and, finally, biological treatment, while disposal is either conducted to a surface water receptor or the treated wastewater is reused for the needs of biological treatment plant. The wastewater from the industries involved in the production and packaging of pomace oil mainly originates from: cooling water from refrigerators of hexane, wastewater from the process of separating the mixture of water, oil and hexane, concentrated vapours coming from extraction and wastewater from neutralisation. The olive–pomace oil industries studied either apply pre-treatment methods, physicochemical and biological treatment or focus on specific wastewater streams.

Solid waste originating from the oil production includes: pomace, olive leaves, inappropriate (damaged) olives, ash from the operation of burners, dust due to burners operation or due to drying of pomace and sludge derived from the evaporation, the precipitation and/or septic tanks. Pomace handling is 100 % undertaken by the olive–pomace facilities, where olive–pomace oil and pomace wood are produced. This is an excellent example of by-product valorisation, since waste produced from one company constitutes raw-material for another. Olive–pomace oil producers buy pomace from olive oil producers and, as a result, olive oil producers are in line with their environmental obligations and have profit at the same time. It is a common practice that pomace oil producers pay olive oil producers with pomace oil or pomace wood instead of money. The evolution of 2-phase decanters resulted in producing pomace with higher humidity (62 % instead of

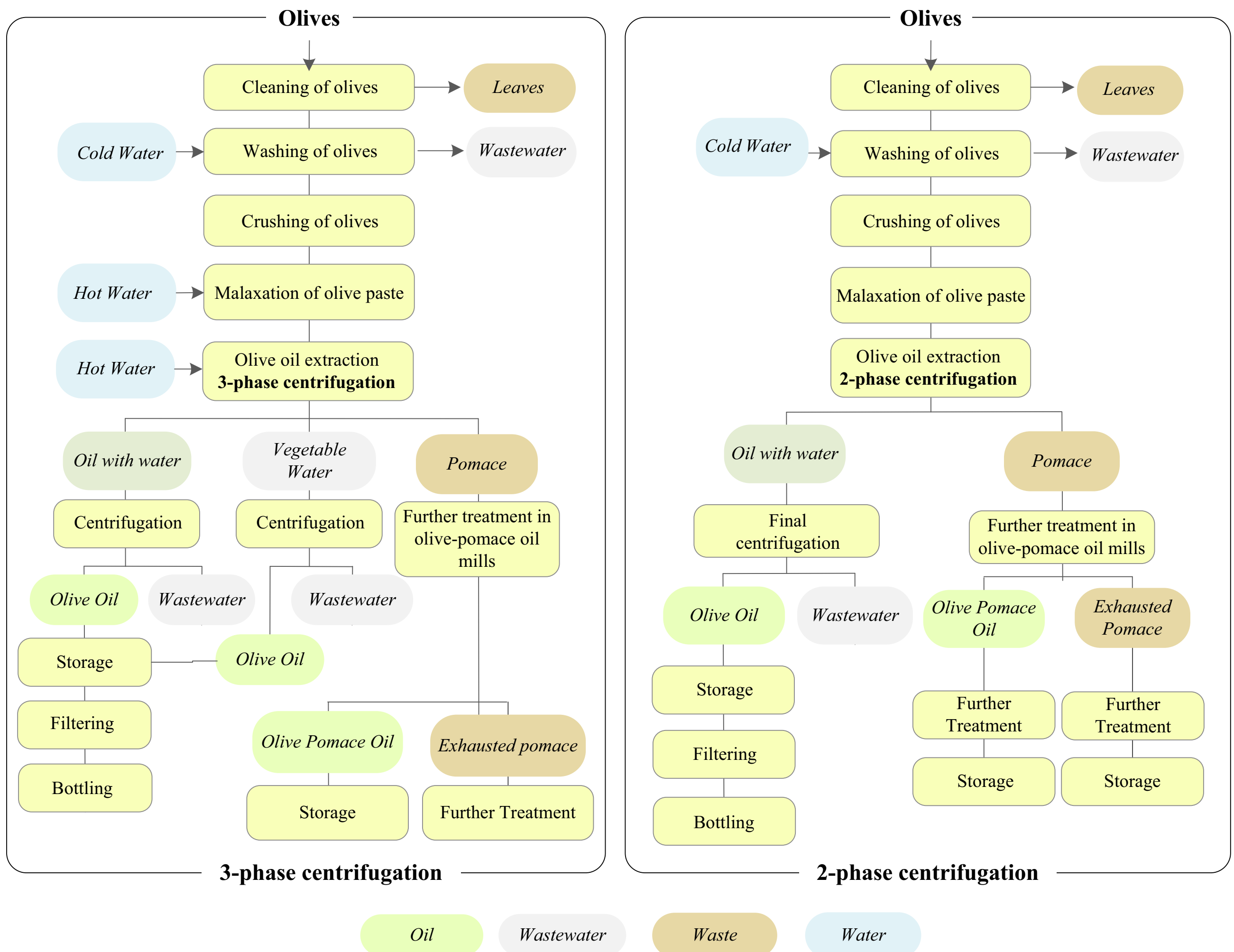

Fig. 2 Key information related to 3-phase and 2-phase centrifuge in OOMs

55 % from three-phase decanters) resulting in proportional increase of energy consumption needed for drying of pomace. This caused an increase of the pomace wood cost. According to *Z8 condition* of the JMD 15/4187/266/11.04.2012, pomace should be treated at olive pomace facilities. Most Greek industrial units use olive leaves as animal feed or as fertilizer or as fuel. Inappropriate olives are available as animal feed or soil improver or for biogas production. The ash from pomace wood burners is disposed with municipal waste or used for fertilisation. Similarly, the sludge resulting from both the production process and the treatment of wastewater is collected, dehydrated and used most of the times (83 %) as a soil improver. One of the industries studied disposes its sludge in landfills and another to authorised companies for further treatment. Despite the fact that according to *Z8 condition* of the JMD 15/4187/266/11.04.2012 sludge from the evaporation ponds should be disposed as soil improver after mixing and dehydration or after alternative treatment methods, it was not possible during the implementation of the current study to record the exact circumstances where this is conducted in Greece. Nevertheless, sludge from evaporation ponds should not be applied directly to soil, since this may entail risks due to toxic effects. Moreover, production of the following types of waste was also noticed: solid residues from oil tanks used for making soap, used resins, bleaching earth and diatomaceous earth used as filtering mediums (which are given to appropriate companies) and dust. In olive pomace oil industries dust is usually collected in cyclones and comes from the dryers of pomace and from steam boilers. Dust from dryers initially undergoes extraction and then is burned along with pomace wood in dryer burners or steam boilers, while dust from steam boilers is burned with pomace wood.

In order to determine further valorisation opportunities for solid waste and wastewater originating from the Greek

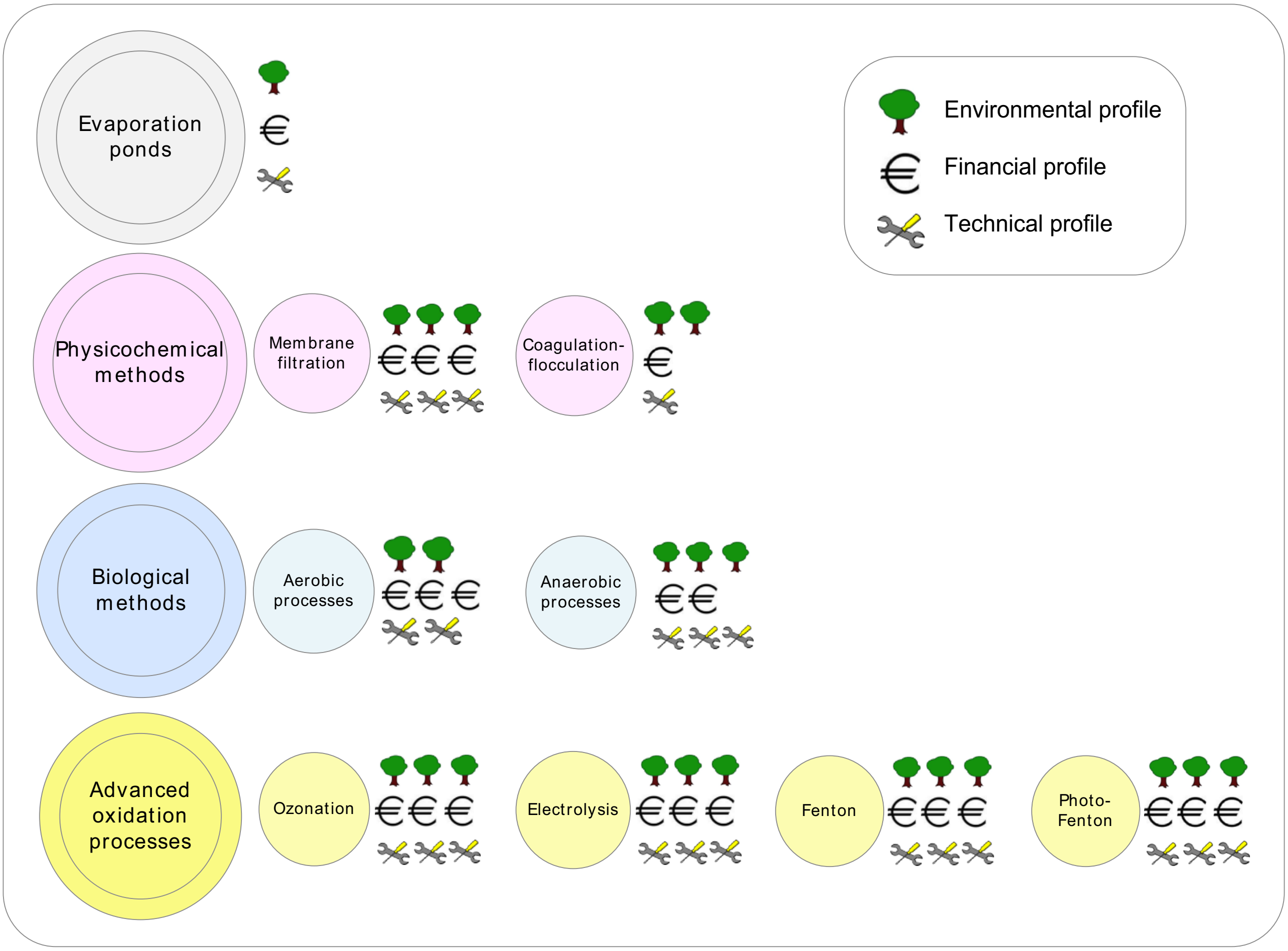

Fig. 3 Environmental, financial and technical profile of the different olive oil wastewater treatment methods

oil industries, a literature review was conducted. As mentioned before, the olive oil production process generates two kinds of residues, the liquid residues (wastewater) and the solid residues, such as pomace, olive stone, olive leaves and small twigs. The valorisation of these residues after proper treatment has been studied extensively and numerous practices have been proposed. Until now, the exploitation of some streams has been successfully incorporated in industrial scale, e.g. pomace valorisation for olive pomace oil production, while for others, such practices have not been integrated into the production process mainly due to concerns related to the potential negative effects from the application or/and due to their low economic feasibility.

In particular, in Greece, as it was recorded, the produced pomace is used for the extraction of olive pomace oil, with the use of solvents, after being subjected to drying. The exhausted olive pomace, given its high calorific value, is used as a fuel in olive mills for the generation of energy through combustion [10, 11]. However, the total energy recovery rate is low considering that most of the energy produced is used in the drying process [12]. Other proposed applications of olive pomace include its use as an adsorbent material for the treatment of heavy metal contaminated water [13] as well as its application to soils for increasing the sorption of pesticides [14, 15]. Bhatnagar et al. [16] has conducted an extended review paper in which a vast majority of adsorbents prepared by utilising different types of olive mill solid waste materials were studied. The authors concluded that the use of such materials as inexpensive adsorbents for removing various pollutants (metals, pharmaceuticals, dyes etc.) from water and wastewater constitutes an attractive feature especially related to the reduction of costs for waste disposal [16].

Other solid residues produced during the olive oil production are the olive leaves and twigs as well as the olive stones. Olive leaves and twigs are widely used as animal feed or for the production of thermal energy [17]. Moreover, olive leaves are used in herbal teas due to their antioxidant properties [17]. Olive stones may be used for the production of energy due to their high calorific value as well as for the production of activated carbon for the removal of dyes [18], heavy metals and other contaminants from water and wastewater [19–26].

Wastewater treatment methods for vegetable water produced during oil production have been reviewed elsewhere [3, 27]. Figure 3 presents in a comparative way the environmental, economical and technical profile of each important wastewater treatment method based on the present work and literature results.

In general, aerobic and anaerobic treatment, including anaerobic co-digestion with other effluents and composting, are predominant, while advanced oxidation processes have attracted much attention, since they result in a high degree of treatment and valorisation [3, 28]. More specifically, olive mill wastewater may be applied to soils, as it is rich in nutrients, after having been subjected to biological treatment for the reduction of its toxicity and phenolic content [29]. For the composting process, olive mill wastewater must be firstly absorbed in a solid substrate [17]. Olive oil by-products may also be used as a nutrient source for the cultivation of edible fungi [30–32]. A promising approach has been proposed by Arvanitis et al. [33] who performed a feasibility study at regional level including the application of ultrafiltration (UF), nanofiltration (NF), and/or reverse osmosis (RO) in order to obtain a higher separation of toxic fraction from the nutritious one. According to the authors the application of the proposed scheme can result in a production of 5 % nutrition fraction which can be used as fertiliser and 15 % of toxic fraction that can be used as herbicide [42]. Such an investment was considered viable for the capacity of 50,000 t/year (50 typical mills) taking into account that the rate of return was acceptable (18 %) [33].

The bioconversion of olive mill wastewater and of other olive by-products for the production of biomolecules, such as biopolymers, enzymes and phenolic compounds, constitutes another valorisation alternative [29]. The production of polysaccharides from the microbiological treatment of olive mill wastewater, such as xanthan which can be used in the food industry as a food thickening agent and stabiliser has been proposed [29]. Furthermore, pectins may be extracted from olive mill wastewater and olive pomace and subsequently used as gelling agents, stabilizers and emulsifiers in the food industry [17, 34–36]. Olive oil by-products may be used as a substrate for the production of enzymes which have applications in the dairy, pharmaceutical, detergent and other industries [37]. Last but not least, both olive mill wastewater and olive pomace contain substantial amounts of phenols possessing valuable antioxidant, anti-inflammatory and antimicrobial properties that can be recovered and used in the food and pharmaceutical industry [17, 29].

The valorisation of olive mill wastewater for dyeing textile materials, such as wool and acrylic fibers, has also been studied [38, 39] based on the fact that they constitute an abundant source of natural dyeing substances. Moreover, olive mill wastewater given its substantial sugar, volatile acid, polyalcohol and fat content may be used as a substrate for biohydrogen, biomethane and bioethanol production [29]. Finally, the use of olive mill wastewater and olive pomace in brick and fired clay masonry units production has been reported to have positive quality and economic results [40–43].

Conclusions

The main products derived from the Greek olive oil production industries include olive oil, refined oils, olive–pomace oil and pomace wood. Other by-products with economic value include pomace which comprises the raw material for olive–pomace oil production, sediment material from oil storage tanks which is sold to soap manufacturing industries and olive leaves which are forwarded as animal feed. The extraction of olive oil is mainly implemented through three-phase or two-phase centrifuge. The method of extracting the oil determines to a great extent both the capacity and the qualitative and quantitative characteristics of the resulting oil, wastewater and solid waste. Concerning wastewater generation, the 3-phase process leads to the generation of three streams, i.e. oil mixed with water, wastewater and pomace, while 2-phase decanters produce only olive oil mixed with water and pomace. Therefore, 3-phase extraction results in higher volumes of wastewater. Vegetable water derived from 3-phase decanters is responsible for the high polluting load of the wastewater. On the basis of the evaluation of data, it was obvious that the prevailing waste treatment method that it is currently applied in Greece includes oil collection, neutralisation of acidity, sedimentation and disposal to open evaporation ponds. This is a basic—level technique and, thus, alternative more advanced treatment options may be applied leading to better environmental protection along with other benefits, e.g. bioenergy. In relation to solid waste management and valorisation, an excellent example of by-product valorisation is pomace processing for olive pomace oil and pomace wood production, since waste generated from one industrial unit constitutes raw-material for another. Moreover, sludge produced from evaporation ponds can be used as soil improver only after mixing and co-composting with other substrates. Apart from the above, alternative valorisation options, such as production of adsorbents, antioxidants, biopolymers, enzymes and dyeing textile materials, which have recently received a great deal of attention in various publications, need to be further developed so as to increase the economic feasibility of these processes towards their industrial use, adding thus more value to olive oil production process.

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