Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1153905

57 (2016) 20639–20645
September

Agronomic and economic implications of using treated olive mill wastewater in maize production

Maria I. Kokkora*, Konstantinos B. Petrotos, Chryssoula Papaioannou, Paschalis E. Gkoutsidis, Stefanos Leontopoulos, Panagiotis Vyrlas

Laboratory of Food and Biosystems Engineering, Department of Agricultural Engineering Technologies, Technological Educational Institute of Thessaly, TEI Campus, Larissa 41100, Greece, Tel. +30 2410 684749; email: mkokkora@teilar.gr (M.I. Kokkora)

Received 24 October 2015; Accepted 3 February 2016

ABSTRACT

Olive mill wastewater (OMWW) is a byproduct of the olive oil extraction process, characterized by high polluting load and polyphenols content. The treatment of OMWW, using microfiltration and XAD4 resin, results in recovery of polyphenols, and also in an effluent (treated OMWW) with decreased organic load and phytotoxic properties, compared to the initial OMWW. The effects of the treated OMWW (T-OMWW) application on maize kernel yield and quality, and soil quality were investigated through a two-year field experiment. T-OMWW was applied by drip irrigation to maize cultivation using two rates of 25–50 t ha^{-1} $year^{-1}$, with the addition of mineral fertilization. Furthermore, a treatment of only T-OMWW applied at the rate of 50 t ha^{-1} $year^{-1}$ and an only mineral fertilization treatment were used. Maize kernel yield and quality were not significantly different between mineral fertilization and T-OMWW application, hence indicating that T-OMWW could fully substitute mineral fertilization under the conditions of our study. Based on the experimental results, an economic analysis was undertaken in order to evaluate the economic implications of T-OMWW application by drip irrigation to maize production. Three scenarios were investigated: (a) mineral fertilization only, (b) T-OMWW application at the rate of 50 t ha^{-1} $year^{-1}$ only, and (c) T-OMWW application at the rate of 25 t ha^{-1} $year^{-1}$ combined with reduced mineral fertilization. The cost analysis showed that T-OMWW application at the rate of 50 t ha^{-1} $year^{-1}$ was the least expensive of the three scenarios investigated, irrespective of the distance between the olive mill and the farm. The use of the farm tractor and tanker for the T-OMWW transportation was more cost effective than hiring a liquid transport company, for distance up to approximately 20 km. For greater distance, hiring a liquid transport company was more economical.

Keywords: Microfiltration; XAD4 resin; Non-conventional liquid fertilizer; Maize kernel yield; Transportation cost

1. Introduction

Olive oil consumption is increasing worldwide, due to its high dietetic and nutritional value. Olive oil extraction involves the generation of a wastewater stream, which constitutes serious environmental problem in the Mediterranean area, due to its high polluting load. Olive mill wastewater (OMWW) is characterized by high COD and BOD, high content of solids and organic compounds, and also phytotoxic

*Corresponding author.

properties and resistance to biodegradation caused by its phenolic compounds [1,2].

Olive oil extraction in Greece is mainly carried out by local olive mills, which in most cases are small or medium enterprises. These olive mills, in order to avoid OMWW treatment costs, usually dispose the OMWW to nearby land. Crop response to untreated OMWW application is variable; research has shown that crop yields may decrease [3], not be influenced [4], or increase [3,5] following OMWW application. Germination problems have also been observed due to phytotoxic effects of the phenolic compounds contained in the OMWW [6,7].

The phenolic compounds contained in the OMWW are natural antioxidants, with commercial and economic interest. Hence, the treatment of OMWW aiming at the recovery of the polyphenols could result in economic benefits for the olive mill. Membrane filtration of OMWW may result in a significant decrease in its organic load and suspended solids content [1,8], and also in polyphenols separation from the mass of waste [9–11]. OMWW treatment with microfiltration resulted in polyphenols separation in the permeate [10]. Polyphenols may then be successfully removed with the use of suitable resins [12–14]. The recovered polyphenols may be utilized in the pharmaceutical, cosmetic, and food industry, whereas the remaining effluent, which will have decreased phytotoxic properties due to the polyphenols removal, could be more safely utilized in agriculture. Research on the agronomic effects of treated OMWW (T-OMWW) application to agricultural soil is limited, and mainly involves OMWW that has been treated by chemical or biological techniques [15–17].

The objectives of this study were: (i) to determine the agronomic effects of two years of T-OMWW application by drip irrigation to maize production and (ii) to evaluate the economics of maize fertigation with T-OMWW.

2. Materials and methods

2.1. Treated olive mill wastewater (T-OMWW)

Two samples of OMWW, approximately 10 t each, were collected within two successive years from a local olive mill in the area of Larissa, Central Greece. Each year, the raw OMWW was initially centrifuged at 1,200 rpm using a rotary finisher bearing a stainless screen with openings of 150 μm diameter. This first step was aimed at separating the suspended solids contained in OMWW, in the form of sludge, in order to avoid clogging of the membrane used in the next step. In the second step, the centrifuged OMWW was filtered using a ceramic microfiltration membrane of 200 nm pore size in order to separate the polyphenols in the permeate from the mass of waste (retentate). The effluent produced as permeate in this step was suitable to be applied through a drip irrigation system, with limited risk of emitters clogging. As a final step, the permeate produced in the second step was passed through a column filled with the XAD4 macroporous resin, which has the ability to retain selectively the polyphenols [13], aiming to recover the polyphenols and minimize any phytotoxic effects of the remaining effluent. The polyphenolic content of the remaining effluent was approximately 20–30% of the initial polyphenolic content of the input material.

The T-OMWW (the remaining effluent of the final stage) was considered for utilization in agriculture as a liquid fertilizer. Some quality properties of the T-OMWW are presented in Table 1 (the values shown are the average of the two samples).

2.2. Field experiment

A two-year field experiment was carried out at the experimental farm of Technological Educational Institute of Thessaly, Larissa, Greece. The topsoil of the experimental site (0–0.3 m depth) was clay loam (41% sand, 20% silt, 39% clay) and in the beginning of the experiment was characterized by almost neutral pH (7.3), electrical conductivity of 723 μS cm^{-1} and $CaCO_3$ of 1.8%.

The experimental design involved four treatments: (i) mineral fertilization only (F), (ii) application of T-OMWW at the rate of 50 t ha^{-1} (50 W), (iii) combined application of T-OMWW at the rate of 50 t ha^{-1} with reduced mineral fertilization (50 W + f), and (iv) combined application of T-OMWW at the rate of 25 t ha^{-1} with reduced mineral fertilization (25 W + f).

The amount of nutrients added with mineral fertilizers in each treatment in both years of experimentation is presented in Table 2. In the first year of the

Table 1
Treated olive mill wastewater (T-OMWW) quality parameters

Properties	Values
pH	5.4
Electrical conductivity (mS cm^{-1})	9.1
Salinity (%)	7.5
Solid residue (%)	7.1
Available P (mg L^{-1})	752.0
Available K (mg L^{-1})	968.0
Mineral N ($NH_4 + NO_3$) (mg L^{-1})	44.7

Table 2
Total amount of T-OMWW and mineral fertilizer nutrients applied in the 2 years of the experiment

		Mineral fertilization ($kg\ ha^{-1}$)			
Treatments	T-OMWW ($t\ ha^{-1}$)	N	P	K	S
F	0	310	78	22	31
25 W + f	50	255	57	22	7
50 W + f	100	255	57	22	7
50 W	100	0	0	0	0

experiment, fertilizer nitrogen was applied as ammonium nitrate (34.5–0–0). In the second year, three fertilizers were used: Pekacid (0–60–20), urea phosphate (17.5–44–0), and ammonium sulfate (21–0–0).

Each year, each treatment was applied to an individual plot of 60 m^2 (6 × 10 m, including eight plant rows), using a complete randomized block design with four replicates. Maize (*Zea mays*) was used as the monitoring crop.

Water, mineral fertilizers, and T-OMWW were applied through a drip irrigation system. Each year, each plot received 300 L of T-OMWW at the rate of 50 $t\ ha^{-1}$ and 150 L for each plot receiving T-OMWW at the rate of 25 $t\ ha^{-1}$. All treatments were irrigated at 100% crop evapotranspiration (ET_c) during the full season, in both years of the experiment. The irrigation applied through the drip system was determined according to FAO-56 methodology [18]. Further details on the irrigation scheme followed can be found in Kokkora et al. [19]. Total watering during the first growing season was 500 mm with 312 mm applied through the drip system for all treatments. Total watering during the second growing season was 576 mm with 480 mm applied through the drip system for all treatments.

Maize kernel yield was determined at harvest. Maize ears were harvested by hand from 10 maize plants from the central four rows of each experimental plot. Maize ears were dried in a ventilated oven at 55℃, until constant weight. After drying, maize kernels were separated from the rest of the ear, weighted, grinded, and then analyzed for protein and starch content, using an automatic near infrared analyzer. Reported kernel protein and starch content were corrected to 0% moisture content.

The effect of each treatment on crop and soil measured variables was assessed by ANOVA at the level of statistical significance of $p < 0.05$, and means were separated by Duncan's multiple range test using the statistical program SPSS (SPSS Inc., Edit. 17.0, Chicago, USA).

2.3. Economic analysis

Based on the results of the field experiment, a cost analysis was undertaken in order to evaluate the economic implications of T-OMWW application by drip irrigation to maize production. Three fertilizing scenarios were investigated: (a) mineral fertilization only, (b) T-OMWW application at the rate of 50 $t\ ha^{-1}\ year^{-1}$ only, and (c) T-OMWW application at the rate of 25 $t\ ha^{-1}\ year^{-1}$ combined with reduced mineral fertilization. Mineral fertilization involved the cost of buying the mineral fertilizers used in our study. T-OMWW utilization involved no buying cost. It was assumed that T-OMWW was provided with no charge by the olive mill. The cost of OMWW treatment was not taken into consideration. This was because the olive mill carries out the treatment procedure described in paragraph 2.1, in order to recover the polyphenols, which are high added-value substances and compensate the treatment expenses and also produce an extra profit to the olive mill. The T-OMWW is of no further use for the olive mill; hence, it is on farmers' disposal free of charge.

The application cost of T-OMWW and mineral fertilization was considered equal, since the application of both fertilizers was carried out using the same drip irrigation system. T-OMWW utilization involved the transport cost from the olive mill to the field. The transport cost was determined considering a distance up to 100 km between the olive mill and the farm, and also two transport options: (a) using the available farm tractor and tanker and (b) hiring a liquid transport company. Farm tanker capacity was considered equal to 10 t, which is the most common case in Greece. The tanker of the liquid transport company was taken equal to 25 t (common capacity of professional tankers).

In the case of using the farm available equipment (farm tractor and tanker), the cost of transport was calculated based on the number of routes, between the olive mill and the farm, necessary to transport the desired amount of T-OMWW according to Eq. (1), with the quotient rounded to the highest integer. Tanker capacity was equal to 10 t. For example, in the case of T-OMWW application at the rate of 25 t $ha^{-1}\ year^{-1}$ (scenario "c"), considering a farm area of 1 ha, then the desired amount of T-OMWW is 25 t and the necessary number of routes is three, whereas in the case of T-OMWW application at the rate of 50 $t\ ha^{-1}\ year^{-1}$ (scenario "b"), considering a farm area of 1 ha, then the desired amount of T-OMWW is 50 t and the necessary number of routes is five. The cost of each route in euros was calculated according to Eq. (2), where d is the distance between the olive mill and the farm (km), AOC is the average operating cost (€ h^{-1}), and AS is the average speed of the farm tractor and tanker (km h^{-1}).

$$\text{Number of routes} = \frac{\text{amount of T} - \text{OMWW}}{\text{tanker capacity}} \tag{1}$$

$$\text{Route cost (€)} = 2 \times \text{d} \times \frac{\text{AOC}}{\text{AS}} \tag{2}$$

In the case of hiring a liquid transport company, the transport cost was given in euros per tonne, based on the distance between the olive mill and the farm (values were estimated by interviewing Greek liquid transport companies). In this analysis, indirect costs or benefits, related for example to potential environmental damage caused by the uncontrolled disposal of the effluent to the environment, were not taken into consideration.

3. Results and discussion

3.1. Agronomic results

Mean maize kernel dry matter (DM) yield for the two years of the study is presented in Fig. 1 (maize kernel DM yield was not significantly different between the two years of experimentation). The effect of T-OMWW application on maize kernel DM yield was not significant (Fig. 1). However, a non-significant trend for lower yield with the application of T-OMWW at the rate of 50 t per ha per year was observed. This finding, which was more obvious in the second year of experimentation, was attributed to potential salinity effects of T-OMWW on the crop [19]. The effect of T-OMWW application on maize kernel protein and starch yield was not significant either (Fig. 2).

The results of T-OMWW application on maize grain yield and quality suggested that T-OMWW can be used as liquid fertilizer in maize production. The conventional application of only mineral fertilizers gave similar results with the only T-OMWW treatment, indicating the potential of mineral fertilizer substitution by T-OMWW, under the conditions of our study. Although not clearly shown within the first two years of T-OMWW application to maize production, it seemed advantageous from an agronomic perspective to apply the T-OMWW at the lower rate of 25 t per ha per year. Further results on the agronomic effects of the two-year T-OMWW application to maize production can be found in Kokkora et al. [19].

3.2. Economic study

Since maize kernel yield and quality were not significantly influenced by the different treatments, it was assumed that the production profit was equal in all cases under study. Hence, the focus of our analysis was the associated fertilization costs.

In the case of fertilization scenario "a": mineral fertilization only, the cost involved was that of buying the fertilizers. The cost of buying the fertilizers used in our study in both years of experimentation is presented in Table 3. It must be noted that all fertilizers were water soluble, as they were applied through the drip irrigation system. In total, the cost of mineral fertilization was estimated at approximately 890€ per ha. It can be seen in Table 3 that fertilizer Pekacid is a

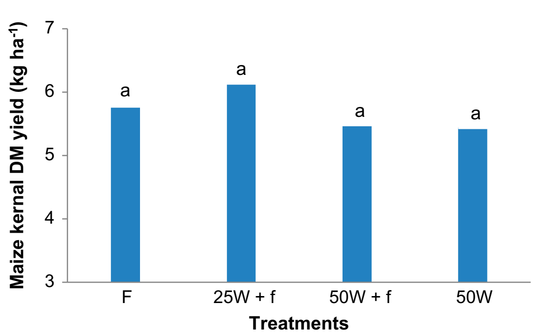

Fig. 1. Mean maize kernel DM yield (in kg per ha) for the two years of experimentation, as affected by the different treatments (F: mineral fertilization only, 25 W + f: 25 t ha^{-1} $year^{-1}$ of T-OMWW plus mineral fertilization, 50 W + f: 50 t ha^{-1} $year^{-1}$ of T-OMWW plus mineral fertilization, 50 W: 50 t ha^{-1} $year^{-1}$ of T-OMWW only).

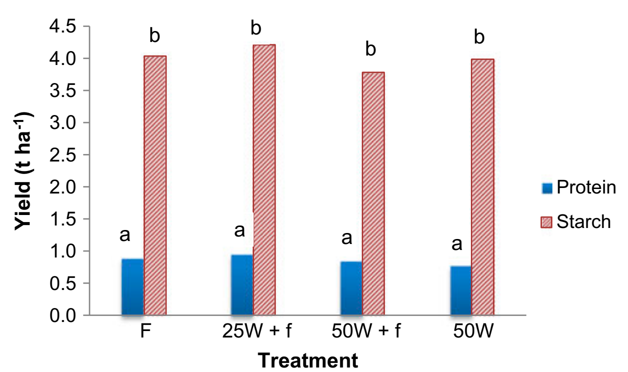

Fig. 2. Mean maize kernel protein and starch yield (in kg per ha) for the two years of experimentation, as affected by the different treatments (F: mineral fertilization only, 25 W + f: 25 t ha^{-1} $year^{-1}$ of T-OMWW plus mineral fertilization, 50 W + f: 50 t ha^{-1} $year^{-1}$ of T-OMWW plus mineral fertilization, 50 W: 50 t ha^{-1} $year^{-1}$ of T-OMWW only).

quite expensive fertilizer. In the case that Pekacid was replaced by triple superphosphate (TSP) (0–46–0), (under the conditions of our study, this replacement was possible due to relatively high soil K availability), then the total cost of mineral fertilization would be 698.91€ per ha for both years of experimentation.

In the case of fertilization scenario "b": T-OMWW application at the rate of 50 t ha^{-1} $year^{-1}$ only, the cost involved was the transport cost from the olive mill to the farm. In the subcase of using the farm available equipment (farm tractor and tanker), the cost of transport was calculated based on Eqs. (1) and (2). The AOC was assessed taking into account the average fuel consumption of the tractor, the cost of fuel, the cost of machinery damage, tire wear costs, and also labor costs. According to the Greek market in June 2015, AOC was estimated equal to 28€ h^{-1}. The AS was estimated equal to 25 km h^{-1}, taking into consideration that the farm tractor and tanker moves into provincial and rural road network. The total transport cost of T-OMWW by the available farm tractor and tanker for both years of experimentation is shown in Fig. 3, in respect to the distance from the olive mill to the farm. In the subcase of hiring a liquid transport company, the transport cost was estimated at 5€ t^{-1} for distance between the olive mill and the farm up to 50 km, and 8€ t^{-1} for a distance between 50 km and 100 km. The total transport cost of T-OMWW by hiring a liquid transport company for both years of experimentation is shown in Fig. 3.

It is evident from Fig. 3 that using the farm tractor and tanker for the T-OMWW transportation was less expensive than hiring a liquid transport company, for a distance up to about 22 km between the olive mill and the farm. For greater distance, the option of hiring a liquid transport company was more favorable from an economical perspective.

The last fertilization scenario "c": T-OMWW application at the rate of 25 t ha^{-1} $year^{-1}$ combined with reduced mineral fertilization, involved two costs; the cost of buying the fertilizers and the transport cost of T-OMWW from the olive mill to the farm. In this case,

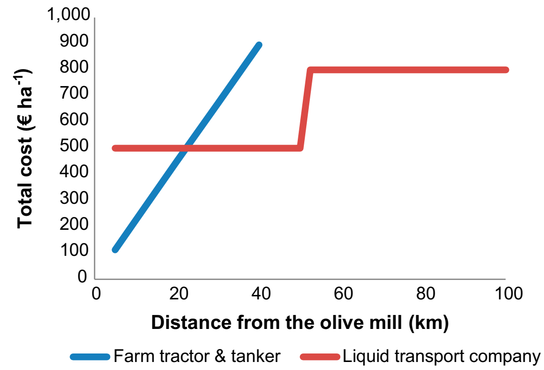

Fig. 3. Total transport cost from the olive mill to the farm: (a) using the farm tractor and tanker and (b) hiring a liquid transport company, for 2 years of T-OMWW application at the rate of 50 t ha^{-1} $year^{-1}$.

the amount of fertilizers used was reduced in comparison to fertilization scenario "a"; therefore, the cost of mineral fertilization was estimated at approximately 710€ per ha, for both years of experimentation (Table 4). Considering again the replacement of Pekacid with the TSP, then the total cost of mineral fertilization would be 514.32€ per ha for both years of experimentation.

The transport cost in this case was calculated again with the same methodology described in scenario "b", considering two transport options, for a total rate of T-OMWW application of 25 t per ha per year. The total cost of buying the mineral fertilizers plus the transport cost of T-OMWW is presented in Fig. 4. It can be seen from Fig. 4 that using the farm tractor and tanker for the T-OMWW transportation was less expensive than hiring a liquid transport company, for a distance up to about 19 km between the olive mill and the farm.

Fig. 5 compares the three scenarios, taking into consideration both options of T-OMWW transportation and the potential for Pekacid replacement by TSP. It can be seen that the application of T-OMWW at the rate of 50 t per ha per year only was the most

Table 3
The amount of fertilizers used in the fertilization scenario "a": mineral fertilization only, in both years of the study, and the respective buying costs according to the Greek market in June 2015

Fertilizers	Cost (€ kg^{-1})	Application rate (kg ha^{-1})	Cost (€ ha^{-1})
Ammonium nitrate	0.48	597.0	286.56
Pekacid	2.20	136.4	300.08
Phosphate urea	0.87	223.1	194.10
Ammonium sulfate	0.33	337.9	111.51
Total cost (2 years)			892.24

Table 4
The amount of fertilizers used in both years of the study in the fertilization scenario "c": T-OMWW application at the rate of 25 t ha^{-1} year^{-1} combined with reduced mineral fertilization, and the respective buying costs according to the Greek market in June 2015

Fertilizers	Cost (€ kg^{-1})	Application rate (kg ha^{-1})	Cost (€ ha^{-1})
Ammonium nitrate	0.48	597.0	286.56
Pekacid	2.20	136.4	300.08
Phosphate urea	0.87	111.6	97.09
Ammonium sulfate	0.33	72.50	23.93
Total cost (2 years)			707.66

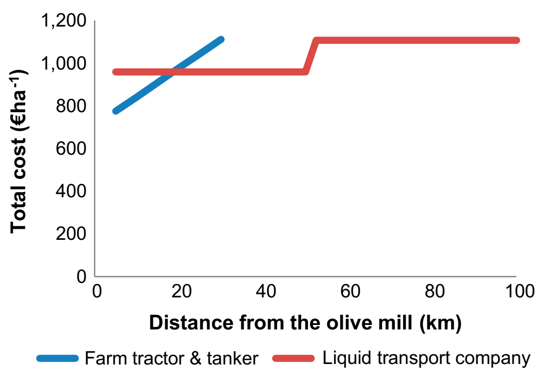

Fig. 4. Total cost of the fertilization scenario "c": T-OMWW application at the rate of 25 t ha^{-1} year^{-1} combined with reduced mineral fertilization, including the cost of buying the mineral fertilizers and the transport cost from the olive mill to the farm: (a) using the farm tractor and tanker and (b) hiring a liquid transport company, for 2 years of T-OMWW application.

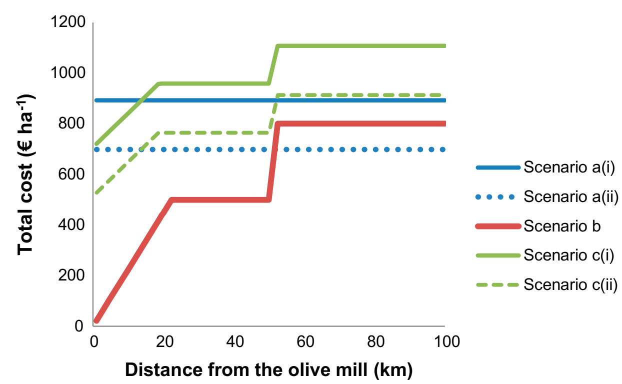

Fig. 5. The variation of the total cost of the fertilization scenarios under study, in relation to the distance from the olive mill to the farm, for both years of the experiment (scenario a(i): mineral fertilization only as applied in the study; scenario a(ii): mineral fertilization only, with TSP replacing Pekacid; scenario b: T-OMWW application at the rate of 50 t ha^{-1} year^{-1}; scenario c(i): T-OMWW application at the rate of 25 t ha^{-1} year^{-1} combined with reduced mineral fertilization as applied in the study; scenario c(ii): T-OMWW application at the rate of 25 t ha^{-1} year^{-1} combined with reduced mineral fertilization, with TSP replacing Pekacid). T-OMWW transport cost is presented using the optimum (less expensive) option of transport (using the farm tractor and tanker or hiring a liquid transport company).

economical option for transport distance up to 50 km. Applying high-priced mineral fertilizers made the application of T-OMWW more advantageous from an economical point of view, even at distance greater than 50 km. The cost of applying only mineral fertilizers was quite similar to the cost of combined T-OMWW at the rate of 25 t ha^{-1} year^{-1} and reduced mineral fertilization scenario, for distances between 10 and 50 km. For distances shorter than 10 km, the combined application of T-OMWW and reduced mineral fertilization was more economical than mineral fertilization only. In general, Fig. 5 shows that using the T-OMWW as liquid fertilizer is a viable option, especially if taking into consideration that the prices of mineral fertilizers keep increasing.

4. Conclusions

This two-year field study provided evidence that the application of T-OMWW to maize production may be a sustainable option from both an agronomic and economical point of view. T-OMWW could fully substitute mineral fertilization under the conditions of our study. T-OMWW application at the rate of 50 t ha^{-1} year^{-1} was the least expensive of the three scenarios investigated, for distance up to 50 km between the olive mill and the farm. The cost of maize fertigation with only mineral fertilizers was similar to the combined T-OMWW and reduced mineral fertilization scenario, for distance up to 50 km. The use of the farm tractor and tanker was found more economical than hiring a liquid transport company, for a transport distance up to approximately 20 km.

Further research on the longer term effects of T-OMWW utilization in agriculture is necessary.

Acknowledgments

This research has been co-financed by the European Union (European Social Fund—ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF)—Research Funding Program: ARCHIMEDES III. Investing in knowledge society through the European Social Fund.

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