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Integrated Assessment of Olive Mill Wastewater as a Sustainable Soil Amendment: Effects on Some Soil Properties in Semi-Arid Agricultural Systems

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ABSTRACT

Managing olive mill wastewater (OMW), a byproduct of olive oil production, is crucial due to its environmental impact, which arises from its high organic content and toxicity. Various treatment approaches are being explored to reduce organic load, mitigate toxins, and investigate potential utilization in irrigation and fertilization, especially in the context of global challenges such as climate change and water scarcity. This study explores the influence of olive mill wastewater (OMW) on soil properties in a semi-arid region. A comparison is drawn between a control system irrigated with the farm's irrigation water without fertilization, and another system incorporating treated olive mill wastewater (OMW). The treated wastewater, subjected to physical, physiochemical, and advanced physiochemical methods, is applied to an experimental field. Cultivation involves two crops, *Vicia faba* (beans) and *Hordeum vulgare* (barley), in both treated and untreated soil. Analysis of various physiochemical parameters reveals that controlled OMW application enhances soil properties and provides essential nutrients for plant growth. The second treatment demonstrates a balanced and positive impact on multiple soil indicators, supporting the economic viability of OMW as a sustainable soil amendment in agriculture. Effective OMW management practices are emphasized, highlighting its potential as a beneficial resource for soil improvement in semi-arid regions, with suggestions for further studies to optimize its utilization and minimize environmental impact.

Keywords: Agricultural sustainability; Environmental impact; Olive mill wastewater (OMW) management; Semi-arid regions; Soil properties.

INTRODUCTION

The prevailing challenge of our era is climate change, manifested through natural calamities like floods, landslides, droughts, storms, and rising sea levels (Moustafa *et al.*, 2023). Human-induced greenhouse gas emissions are the primary driver behind the escalating global warming, leading to significant changes in Earth's climate and subsequent environmental repercussions. According to the Intergovernmental Panel on Climate Change, temperatures rose by 1°$_C$ above pre-industrial levels in 2017, and projections indicate a potential increase of 3.5°$_C$ by 2100. These alterations will have a profound impact on communities worldwide, causing a 20% reduction in water availability (Ungureanu *et al.*, 2020). The Mediterranean region expects changes in precipitation patterns, decreased rainfall, and elevated temperatures due to climate change (Rocha *et al.*, 2020).

Global water scarcity, a hindrance to achieving Sustainable Development Goals, results from a combination of local and global factors (Dolan *et al.*, 2021). Water scarcity, characterized by demand exceeding supply, leads to inadequate access to safe water, negatively affecting both human well-being and the environment (Rosa *et al.*, 2020). Approximately 20 million hectares of fertile land degrade annually, posing a threat to livelihoods, with one-third of agricultural land degrading over the past 40 years (Abdelrahman, 2023). Drylands, covering almost 40% of Earth's land area and sustaining around two billion people, face challenges to food security due to factors like land use, climate change, and soil erosion (Abuzaid *et al.*, 2021). Deserts, with limited vegetation, expand at ecological and social costs (Wu *et al.*, 2023).

Olive trees, crucial in the Mediterranean region, constitute 97% of global cultivation (Foti *et al.*, 2021). The cultivation of the olive tree (*Olea europaea L.*) for olive oil production is one of the oldest agricultural practices. Olive oil, valued for its nutritional content and health benefits, is a staple in the Mediterranean diet and is predominantly produced in the Mediterranean region, Europe, the Middle East, the United States, Argentina, and Australia (Sygouni *et al.*, 2019).

The process of extracting olive oil involves various stages such as washing the olives, crushing, malaxation for emulsion breakdown, and ultimately separating and extracting the oil. Technological advancements and increased oil output over time have improved olive oil extraction procedures, enhancing the overall quality of the end product (Abou-Zaid, 2021). However, the extraction of olive oil generates a byproduct known as olive mill wastewater (OMW), a dark, brown liquid with a pH range of 3–6. It contains a stable emulsion of vegetative water, water added during processing, olive fruit, residual oil, and olive pulp fragments (Shabir *et al.*, 2022). Due to its substantial pollutant content,

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OMW poses a significant environmental threat in olive oil-producing countries. The composition of OMW is influenced by extraction technology, processed fruits, and processing conditions, making its direct industrial use as a raw material challenging (Chatzistathis *et al*., 2021). Phenolic contents, including tannins and anthocyanins, are among the problematic components of olive mill waste effluents. OMW has high chemical oxygen demand and biological oxygen demand levels, indicating significant organic pollution (Nunes *et al*., 2018; Cecchi *et al*., 2018; Tufariello *et al*., 2019; Al-Qodah *et al*., 2022).

In the agricultural lands of Mediterranean regions, OMW has been considered as a potential organic fertilizer due to its relatively high organic content and nutrient composition, particularly potassium and phosphorus (Magdich *et al*., 2020). The olive oil industry generates substantial wastewater and solid waste, presenting environmental challenges (Martins *et al*., 2021).

OMW comprises water (83–94% w/w) and organic components (4–18% w/w), including sugars, tannins, polysaccharides, phenolic compounds, organic acids, and lipids (Shabir *et al*., 2023; Tundis *et al*., 2020; Domingues *et al*., 2021; Ramzan *et al*.,2024). The proper disposal of OMW can have positive environmental effects, promoting plant development and serving as a soil conditioner, fuel, source of valuable products (such as methane, biogas, bihydrogen), compost, or as a starting material for the production of essential goods like antioxidants and enzymes. Additionally, olive mill solid residue has the potential to remove heavy metals through biosorption (Khalil *et al*., 2021). OMW can contribute to a circular economy and serve as a source of polyphenols for plant protection, potentially replacing chemical pesticides (Silvestri *et al*., 2021; Leontopoulos *et al*., 2020). This study focuses on the reuse and treatment of olive mill wastewater, evaluating various treatment technologies and their impacts on the soil.

MATERIALS AND METHODS

Experimental System

This study aimed to compare two systems: the first one use irrigation water without fertilization and the second use the treated olive mill wastewater (OMW) with different stages. Olive mill wastewater (OMW) was freshly collected from an olive mill plant near the Camps of Arish University. The plant's outlet was transported to an uncovered concrete tank, at the Faculty of Agricultural Sciences, and diluted with 50% water before experimentation. For each crop, a randomized complete block design (RCBD) with 4 treatments and 3 replicates (12 experimental units) were used.

Field Experimental Design

Soil preparation for planting occurred during the winter season in November 2022, with two crops utilized: (*Vicia faba*) beans and (*Hordeum vulgare*) barley. Standard agricultural practices were followed throughout the growing season. Each crop, with all its treatments, was planted in a 42 m² area (7 × 6 m with 5 rows), and the row spacing was 30 cm. Micro-irrigation was employed, and treated OMW application commenced one month after planting. Irrigation frequency was twice a week with a volume of 5L/42m²/week/crop until crop harvesting.

Olive mill wastewater treatment

Primary treatment (physical treatment)

This physical treatment phase aimed to remove heavy suspended and floating solids through sedimentation, flotation, and filtration. The treated water from this step (A_1) was used in the irrigation system.

Secondary treatment (physiochemical treatment)

This step targeted the elimination of remaining dissolved organic matter. The wastewater was subjected to aerobic conditions with continuous air supply and stirring for 8 hrs daily for 3 weeks. After filtration, the filtrate was stored for an additional 3 weeks under anaerobic conditions. The last filtrate was treated with 60g/100 L of $Ca(OH)_2$ as a coagulant and used in the irrigation system (A_2).

Advanced physiochemical treatment

The last filtrate underwent treatment with granules activated carbon (GAC) as an adsorbent (80g/100 L), followed by filtration after 3 weeks. The treated water was used in the irrigation system (A_3).

Soil Samples

Soil samples were collected from the high-density root zone (30 cm under the dripper) after harvesting using a soil auger. Samples were air-dried, sieved (2.0 mm), and then analyzed for physiochemical parameters.

Physicochemical Analysis of Soil Samples

Soil samples were transported to a central laboratory at Zagazig University for analysis using analytical-grade reagents. The analyses include the following:

Physical Characteristics

All soil samples, including the control irrigated with water from the farm (B) and treatment samples (A1–A3), were analyzed for physical properties. The following parameters were assessed:

pH, measured using a glass electrode pH meter in a 1:2.5 soil-to-water suspension, following the method described by Cottenie *et al.* (1982). Electrical Conductivity (EC) was determined in soil water extracts (1:1) using a conductivity bridge, as outlined by Jackson (1973). Organic Matter (OM), Quantified using the Walkley and Black method, as described by Jackson (1973). While, organic carbon (OC): calculated based on organic matter content.

Chemical Characteristics

The chemical analysis of soil focused on both macro- and micronutrients, as well as heavy metals. The parameters analyzed included: Available Nitrogen (N): Quantified according to Cottenie *et al.* (1982), where 5 grams of each soil sample was shaken with 50 ml of 2 N KCl solution, filtered, and analyzed using the Kjeldahl apparatus. Available phosphorus (P), was determined using the method of Watanabe and Olsen

(1965), where 5 grams of soil was shaken with 50 ml of 0.5 M $NaHCO_3$ solution (pH 8.5) containing activated charcoal, then filtered after 30 minutes. Meanwhile, soluble cations and anions including sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-), chloride (Cl^-), and sulfate (SO_4^{2-}) were analyzed in soil water extracts at a 1:1 ratio following the procedure outlined by Black *et al.* (1968). Sodium and potassium concentrations were determined using flame photometry as described by Cottenie *et al.* (1982). Calcium and magnesium concentrations were evaluated using the versenate method according to Jackson (1973). Micronutrient contents including iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), and boron (B) were analyzed. Heavy Metals: Lead (Pb), cadmium (Cd), nickel (Ni), cobalt (Co), and chromium (Cr) were quantified using atomic absorption spectrophotometry in accordance with AOAC methods (1984).

Other Analyses

Total Phenolic Compounds (TPC): Extracted from soil using a mixture of 96% ethanol, double-distilled water, and acetic acid in a volume ratio of 70:28:2 (v/v/v). The soil-to-extraction mixture ratio was maintained at 1:10 (w/v). Samples were shaken in polyethylene bottles for 1 hour at 40 rpm, filtered through cellulose filters, and analyzed spectrophotometrically by measuring absorbance at 730 nm using catechin solution as a standard, following Singleton and Rossi (1965) and Hruszka (1982). Mechanical analysis of soil particle size distribution was also determined to classify soil type based on the pipette method described by Piper (1951).

Statistical Analysis

Statistical analysis was performed on all data obtained to assess the significance of differences between the control and treatment groups. Each parameter was measured in replicates to ensure reliability and accuracy of the results. Data represented in means ± standard deviation (SD). Mean comparisons were conducted using ANOVA test followed by Duncan's Multiple Ranges Test at a 5% probability level, following Duncan's methodology (1958).

RESULTS

Soil characterization was summarized in Table (1) in which variations in the percentages of sand, silt, and clay components were recorded. The control group (B) exhibited a composition of (93.22%) sandy, (5.52%) silty, and (1.59%) clay, classifying it as predominantly sandy soil. In contrast, treatments A_1, A_2, and A_3 showed noticeable changes in these percentages. Treatment A_3, in particular, displayed a composition of (90.56%) sand, (6.18%) silt, and (3.25%) clay, although it still fell within the sandy soil category. Table (1) indicated that all soil samples had a sand texture. Despite this commonality, there were variations in the composition of each treatment, with notable differences, particularly in the control group (B). The control group had the highest sand content at (96.71%), and its silt and clay percentages were the lowest among the samples, recorded at (1.58%) and (1.67%), respectively.

The soil analysis for cultivated *Vicia faba* (Table 2) recorded the following: the pH values show a slight decrease in treatment A_1 (7.66) compared to the control (7.75), indicating a potential acidifying effect of the treatment. However, A_2 (7.69) and A3 (7.72) exhibit pH values closer to the control. For EC, treatment A1 recorded a notable decrease (1.79 dS/m) compared to the control (2.30 dS/m). This reduction may indicate lower salinity levels, which can be beneficial for plant growth. In contrast, A_2 and A_3 have EC values similar to or higher than the control. Conversely, there is a relative increase in OM, OC, N, P, and K in treatment A_1 compared to the control (B), where, treatment A1 exhibits a significant increase in organic matter (3.79 g/kg), organic carbon (2.20 g/kg), N content (29.93 mg/kg), P level (13.74 mg/kg), and K level (88.52 mg/kg) compared to the control (3.05 g/kg OM and 1.77 g/kg OC, 23 mg/kg N, 8.72 mg/kg P and 75.08 mg/kg K). This may reflect the significant effect of treatment A1 that enhances soil fertility through increased organic content and nutrient content (Table 2). Meanwhile, treatments A_2 and A_3 also show increases in OM and OC, and the measured nutrient contents but not as pronounced as in A1, indicating that while they contribute positively, A_1 is the most effective treatment for enhancing these parameters.

The effectiveness (%) of different treatments of olive mill wastewater (OMW) on measured soil parameters for the cultivated bean plant is presented in Figure (1A-C). The data reveal varying degrees of effectiveness among the treatments in enhancing nutrient availability, specifically nitrogen (N), phosphorus (P), and potassium (K). Treatment A1 demonstrated the highest percentage effect across all three nutrients, suggesting it is the most effective treatment for improving soil fertility.

Treatment A_1 significantly ($p \leq 0.05$) enhanced soil characteristics, with relative increases in effectiveness for organic matter (OM) and organic carbon (OC) of 24.26% and 24.29%, respectively. Similarly, treatment A_2 showed comparable values for OM and OC, with increases of 24.92% and 24.86%, respectively. For nitrogen content, treatment A_1 exhibited a substantial percentage effect of 30.13%, outperforming treatment

Table (1): Particle size distribution and texture grade of experimental soil treated by olive mill wastewater (OMW) across different treatments and cultivated crops (*Vicia faba / Hordeum vulgare).*

Cultivated crops	Treatment applied*	Particle size distribution (%)			Texture grade
		Sand	Silt	Clay	
Vicia faba / Hordeum vulgare	**B**	96.71	1.58	1.67	Sandy
	A1	92.82	4.5	2.67	
	A2	93.01	6.25	1.82	
	A3	92.38	5.14	2.47	

*B Control, A_1 Primary treatment; A_2 Secondary treatment; A_3 Advanced treatment.

Table (2). Physiochemical characterization of experimental soil treated by olive mill waste-water (OMW) across different treatments and cultivated bean crop (*Vicia faba*).

Treatment Applied †	pH	EC (dS m^{-1})	O.M (g Kg^{-1})	O.C (g Kg^{-1})	N (mg Kg^{-1})	P (mg Kg^{-1})	K (mg Kg^{-1})
B	7.75±0.02 ^{a}	2.30±0.10 ^{a}	3.05±0.01 ^{b}	1.77±0.01 ^{b}	23.0±5.61 ^{a}	8.72±0.33 ^{d}	75.08±0.32 ^{d}
A1	7.66 ±0.02 ^{c}	1.79 ±0.02 ^{b}	3.79±0.1 ^{a}	2.20±0.01 ^{a}	29.93±0.18 ^{a}	13.74±0.40 ^{a}	88.52±0.45 ^{a}
A2	7.69 ±0.04 ^{bc}	2.28 ±0.02 ^{a}	3.81±0.1 ^{a}	2.21±0.01 ^{a}	28.53±0.08 ^{a}	11.71±0.19 ^{b}	86.31±0.24 ^{b}
A3	7.72 ±0.02 ^{ab}	1.66 ±0.001 ^{c}	3.46±0.3 ^{ab}	2.0±0.2 ^{ab}	25.36±0.33 ^{a}	10.61±0.21 ^{c}	78.66±0.27 ^{c}

†Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly ($p \leq 0.05$) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

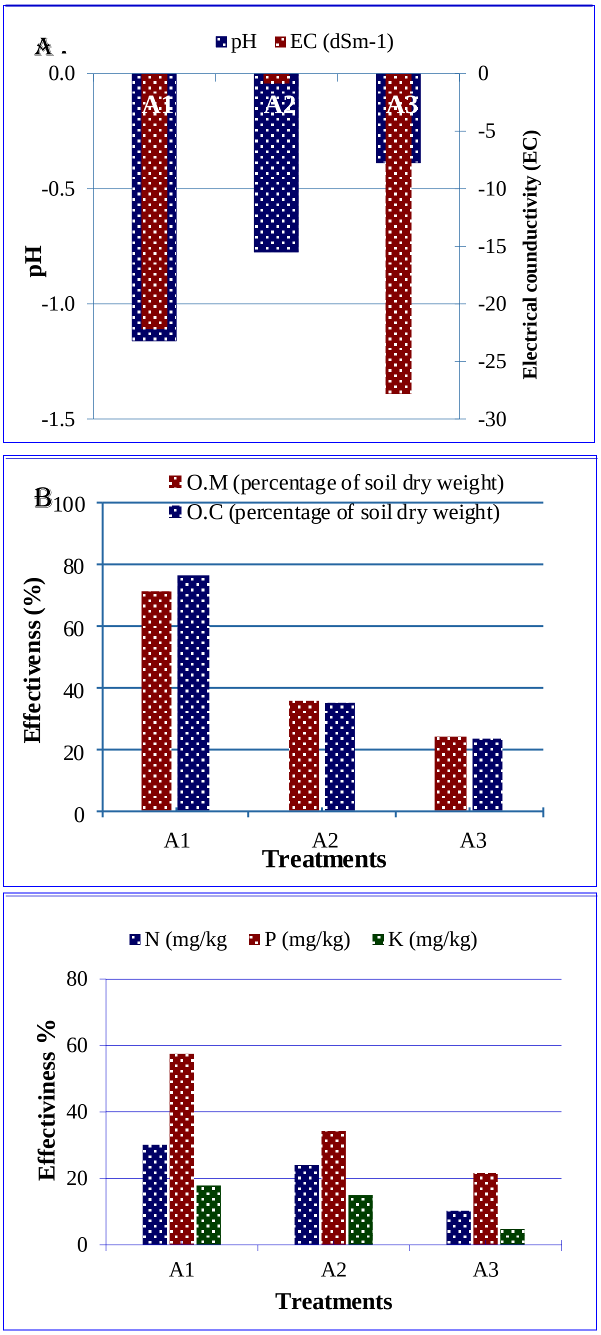

Figure (1): Effectiveness (%) of different treatments of olive oil wastewater on soil characterization. A, pH and EC; B, OM and OC; C, N, P and K content for bean plant.

A_2, which recorded a lower percentage effect of 24.04%. Meanwhile, treatment A3 had the lowest percentage effect on nitrogen at 10.26%, indicating minimal enhancement of nitrogen availability.

For phosphorus, treatment A_1 achieved a particularly high percentage effect of 57.57%, which is noteworthy. Treatment A_2 showed a moderate increase of 34.29% in phosphorus levels, while treatment A_3 recorded the lowest percentage effect at 21.67% (Fig. 1C). Concerning for potassium, treatment A1 recorded the highest percentage effect at 17.90%, followed by A_2 at 14.96%, and A3 at 4.77%.

The results in Table (3) and Figure (2A-C) reveal soil characterization across different treatment barley as cultivate plant. The data showed substantial decrease in pH and an increase in EC values in treatment A_1 compared to the control, accompanied by notable rises in OM, OC, N, P, and K. Particularly noteworthy, there are significant effect on OM and OC, reaching up to (71.43% and 76.99%) respectively, with a note that the values of N and P are approximately equal, being (51.17mg/kg) and (51.38 mg/kg), respectively, compared to the control (Fig. 2C). Meanwhile, treatment A_2 also shows considerable alterations, with a moderate rise in pH and EC compared to the control. Similarly, there are noticeable increases in OM, OC, N, P, and K, although slightly lower compared to A_1. The highest percentage effect increase was observed in OM and OC of value 35.71% and 35.40%, respectively.

In treatment A_3, changes were also evident, but less pronounced. A_3 displayed a moderate rise in pH and EC compared to the control, accompanied by increases in OM, OC, N, P, and K, albeit at lower levels compared to A_1 and A_2. The percentage effect increases for various parameters ranged from (12.18% to 23.98%), with OM and OC showcasing the highest effects at (23.98%) and (23.89%), respectively.

From the above, it is evident that treatments A_1, A_2, and A_3, in terms of their effect on the chemical properties, can be arranged in ascending order based on the average percentage effect for all tested parameters (OM, OC, N, P, K) for each treatment: $A_1 > A_2 > A_3$ with values of (54.33, 24.14, and 13.78), respectively.

For *Vicia faba*, the data of soil analyses that presented in Table (4) and Figure (3) indicate significant increases in all measured parameters, with varying effectiveness percentages observed among the treatments. The A_1 treatment recorded the highest values for several measured elements, including sodium (Na^{+}) at 39.06%, potassium (K^{+}) at 65.38%, calcium (Ca^{2+}) at 58.01%, magnesium (Mg^{2+}) at 115.54%, bicarbonate (HCO_3^{-}) at 69.67%, chloride (Cl^{-}) at 62.58%, and sulfate (SO_4^{2-}) at 58.92%. In contrast, treatment A_2 demonstrated moderate increases

Table (3): Chemical properties of experimental soil treated by olive mill wastewater (OMW) in case of barley.

Treatment†	pH	EC (dS m^{-1})	OM (g Kg^{-1})	OC (g Kg^{-1})	N (mg Kg^{-1})	P (mg Kg^{-1})	K (mg Kg^{-1})
B	7.53 ±0.02 ^{b}	1.56 ±0.06^{d}	1.96±0.1^{c}	1.13±0.1 ^{c}	16.26±0.38 ^{d}	7.61±0.34 ^{d}	60.34 ±0.15 ^{d}
A1	7.52±0.10^{ab}	2.46 ±0.05^{a}	3.36±0.4^{a}	2.0 ±0.3 ^{a}	24.58±0.35 ^{a}	11.52 ±0.22 ^{a}	70.79±0.23 ^{a}
A2	7.63 ±0.02^{a}	1.90±0.07^{b}	2.66±0.1^{b}	1.53 ±0.01 ^{b}	21.82±0.20 ^{b}	9.73±0.17 ^{b}	67.98±0.30 ^{b}
A3	7.60±0.03^{ab}	1.75 ±0.04^{c}	2.43±0.3^{b}	1.40 ±0.2 ^{b}	18.25 ±0.66 ^{c}	8.78 ±0.29 ^{c}	65.09±0.17 ^{c}

†Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly ($p \leq 0.05$) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

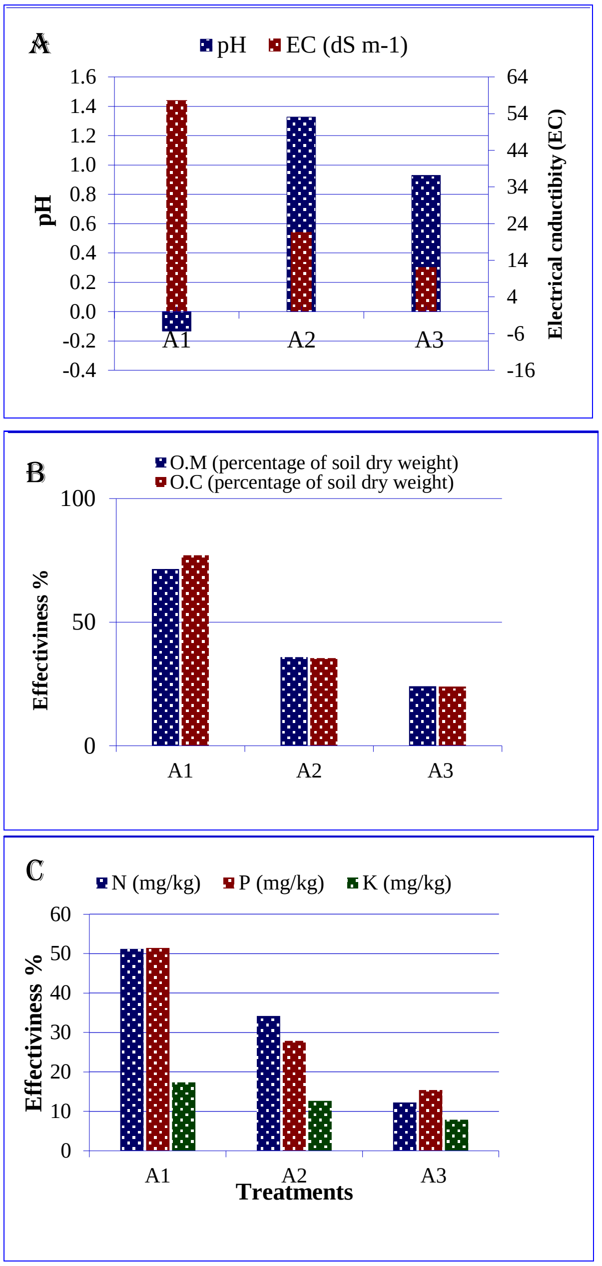

Figure (2): Effectiveness (%) of different treatments of olive oil wastewater on soil characterization. A, pH and EC; B, OM and OC; C, N, P and K content for cultivated barley plant.

in certain parameters, notably potassium (K^{+}) at 59.62% and chloride (Cl^{-}) at 43.76%, while exhibiting lower effects on other elements. Conversely, treatment A_3 showed minimal changes or even decreases in specific elements, particularly sodium (Na^{+}) at 4.70% and chloride (Cl^{-}) at 7.61%. The most significant effect recorded for A_3 was in potassium (K^{+}), with an increase of 48.08%. Based on these results, it is evident that the treatments can be ranked in ascending order of their effect on the availability of nutrient elements (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, HCO_3^{-}, Cl^{-}, and SO_4^{2-}). The average percentage effects for each treatment are as follows: $A_1 > A_2 > A_3$, with values of 67.02%, 35.92%, and 25.01%, respectively. This ranking highlights the superior effectiveness of treatment A_1 in enhancing nutrient availability for *Vicia faba*, suggesting that it may be the most beneficial approach for optimizing growth and nutrient uptake.

Soil analyses conducted with barley plants cultivated under different treatments of olive mill wastewater (OMW) (Table 5) demonstrated significant differences in ion concentrations among the treatments, as demonstrated by the effectiveness percentages presented in Figure (4). Treatment A_1 has the highest sodium concentration (7.90 ± 0.12 m mole/L), significantly greater than the control (B) and treatment A_3 (5.40 ± 0.02 mmole/L). However, treatment A_2 also shows a high sodium concentration (7.87 ± 0.04 mmole/L), similar to A1, indicating effective sodium uptake or retention in these treatments.

For K^{+}, all treatments show similar concentrations, with no significant differences among them (A_1: 0.986 ± 0.001, A_2: 0.946 ± 0.01, B: 0.966 ± 0.01). Meanwhile, treatment A_3 has a significantly lower potassium concentration (0.670 ± 0.05 m mole/L). However, treatment A_1 shows the highest for calcium concentration (7.820 ± 0.29 m mole/L), which is significantly greater than treatments B and A_3. Ttreatment A_2 also has a relatively high calcium concentration (7.396 ± 0.08 m mole/L), but it is significantly lower than A_1.

In the same pattern, treatment A_1 shows the highest magnesium concentration (7.22 ± 0.28 m mole/L), which is significantly higher than treatment A_3 (4.75 ± 0.20 mmole/L). Meanwhile, treatments B and A_2 show similar magnesium concentrations, but both are lower than A_1. For bicarbonate (HCO_3^{-}), treatment A1 has the highest bicarbonate concentration (8.47 ± 0.14 m mole/L), significantly higher than all other treatments. Treatment A_2 shows a moderate bicarbonate level (8.00 ± 0.14 m mole/L), while treatment B has a lower concentration (6.81 ± 0.14 mmole/L). For chloride and sulfate, treatment A_1 exhibits the highest concentration (8.69 ± 0.43 and 8.88 ± 0.04 mmole/L, respectively), significantly greater than all other treatments.

For effectiveness of OMW treatments for barely plant (Fig. 4), treatments A_1 and A_2, generally show positive values for cation and anion levels (Na^+, K^+, Ca^{2+}, Mg^{2+},HCO_3^-, Cl^-, SO_4^{2-}), except for K^+ in treatment A_2, compared to control and treatment A_3. A1 treatment recorded the highest value of these ions with percentages of 41.07%, 2.07%, 17.84%, 24.27%, 24.38%, 28.17% and 36.62 % for Na^+, K^+, Ca^{2+}, Mg^{2+} , HCO_3^-, Cl^- and SO_4^{2-}, respectively). Meanwhile, treatment $A_{3,}$ showed decreases in the levels of all measured ions compared to control.

From the above, it is evident that treatments A_1, A_2, and A_3, in terms of their effect on the chemical properties, can be arranged in ascending order based on the average percentage effect for all tested parameters (Na^+, K^+, Ca^{2+}, Mg^{2+},HCO_3^-, Cl^-, SO_4^{2-}) for each treatment: $A_1 > A_2 > A_3$ with values of (24.92, 22.29, 13.94), respectively.

In Table (6) and Figure (5), treatment A_1 showed a substantial increase in the levels of micronutrient (Fe, Zn, Cu, Mn, and B) compared to the control (B), indicating percentage effect increases of (62.87%, 74.54%, 112.20%, 31.54%, and 77.42%), respectively. A_2 and A_3 also exhibited increases in these micronutrients,

Table (4). Cations and anions of experimental soil treated by olive mill wastewater (OMW) in case of beans

Treatment applied	Na^+ (m mole L^{-1}) *	K^+ (m mole L^{-1}) *	Ca^{+2} (m mole L^{-1}) *	Mg^{+2} (m mole L^{-1}) *	HCO^{3-} (m mole L^{-1}) *	Cl^- (m mole L^{-1}) *	$SO4^{-2}$ (m mole L^{-1}) *
B	5.53±0.18 ^{b}	0.52±0.04 ^{b}	5.12±0.63 ^{c}	3.86±0.09 ^{c}	4.88±0.18 ^{c}	4.73±0.31 ^{c}	5.55±0.13 ^{c}
A1	7.69±0.16 ^{a}	0.86±0.04 ^{a}	8.09±0.19 ^{a}	8.32±0.51 ^{a}	8.28±0.73 ^{a}	7.69±0.47 ^{a}	8.82±0.47 ^{a}
A2	5.58±0.07 ^{b}	0.83±0.02 ^{a}	7.28±0.20 ^{b}	6.06±0.68 ^{b}	6.27±0.06 ^{b}	6.80±0.25 ^{b}	6.63±0.30 ^{b}
A3	5.27±0.14 ^{b}	0.77±0.17 ^{a}	6.73±0.55 ^{b}	5.64±0.21 ^{b}	5.84±0.62 ^{bc}	5.09±0.44 ^{c}	6.52±0.10 ^{b}

Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly ($p \leq 0.05$) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

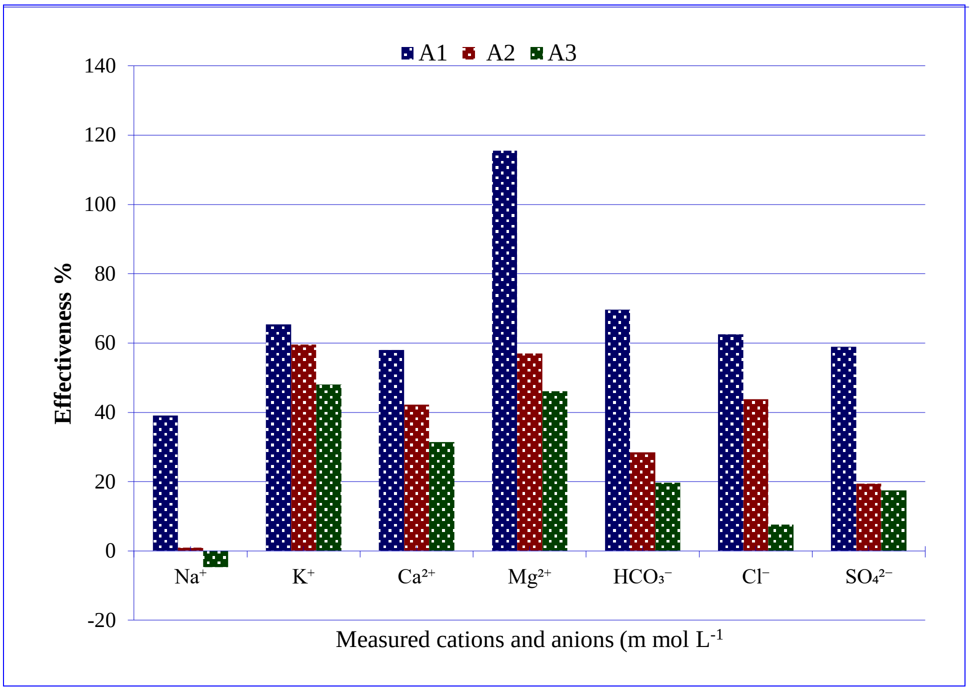

Figure (3):. Effectiveness % of different treatments of olive oil wastewater on cations and anions of soil in which *Vicia faba* was cultivated.

Table (5). Cations and anions of experimental soil treated by olive mill wastewater (OMW) in case of barley.

Treatment applied†	Na^+ (m mole L^{-1})	K^+ (m mole L^{-1}) *	Ca^{+2} (m mole L^{-1}) *	Mg^{+2} (m mole L^{-1}) *	HCO^{3-} (m mole L^{-1}) *	Cl^- (m mole L^{-1}) *	$SO4^{-2}$ (m mole L^{-1}) *
B	5.60±0.54 ^{b}	0.966±0.01 ^{a}	6.636±0.23 ^{c}	5.81±0.01 ^{b}	6.81±0.14 ^{c}	6.78±0.16 ^{b}	6.50±0.20 ^{b}
A1	7.90±0.12 ^{a}	0.986±0.001 ^{a}	7.820±0.29 ^{a}	7.22±0.28 ^{a}	8.47±0.14 ^{a}	8.69±0.43 ^{a}	8.88±0.04 ^{a}
A2	7.87±0.04 ^{a}	0.946±0.01 ^{a}	7.396±0.08 ^{b}	7.14±0.25 ^{a}	8.00±0.14 ^{b}	8.62±0.29 ^{a}	8.74±0.21 ^{a}
A3	5.40 ±0.02 ^{b}	0.670±0.05 ^{b}	5.116±0.20 ^{d}	4.75±0.20 ^{c}	6.34±0.17 ^{d}	6.48±0.24 ^{b}	5.79±0.03 ^{b}

†Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly ($p \leq 0.05$) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

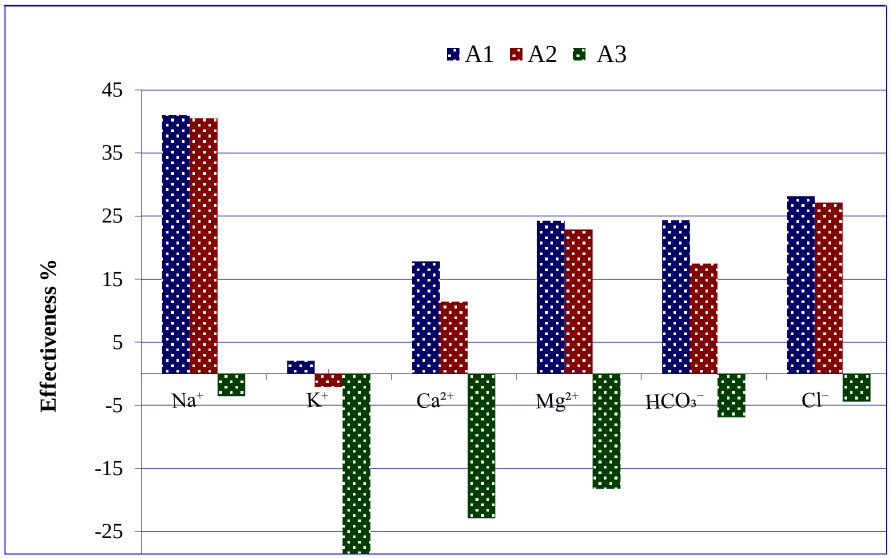

Figure (4). Effectiveness % of different treatments of olive oil wastewater on cations and anions of soil in which barely was cultivated.

Table (6):. Effects of olive mill wastewater (OMW) treatment applications on soil micronutrient levels in *Vicia faba* cultivation.

Treatment applied	Micronutrient measured (mg/kg)				
	Fe (mg Kg^{-1})	**Zn (mg Kg^{-1})**	**Cu (mg Kg^{-1})**	**Mn (mg Kg^{-1})**	**B (mg Kg^{-1})**
B	239.66 ^{d} ±4.50	49.06 ^{d} ±1.94	18.03 ^{d} ±0.08	123.66 ^{c} ±4.73	3.10 ^{c} ±0.17
A1	390.33 ^{a} ±6.11	85.63 ^{a} ±2.83	38.26 ^{a} ±1.70	162.66 ^{a} ±7.09	5.50 ^{a} ±0.10
A2	358.66 ^{b} ±3.21	76.36 ^{b} ±1.58	31.20 ^{b} ±1.72	147.66 ^{b} ±2.08	4.36 ^{b} ±0.38
A3	319.00 ^{c} ±3.03	56.76 ^{c} ±1.30	23.63 ^{c} ±0.60	142.00 ^{b} ±2.06	3.26 ^{c} ±0.11

[†]Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly ($p \leq 0.05$) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

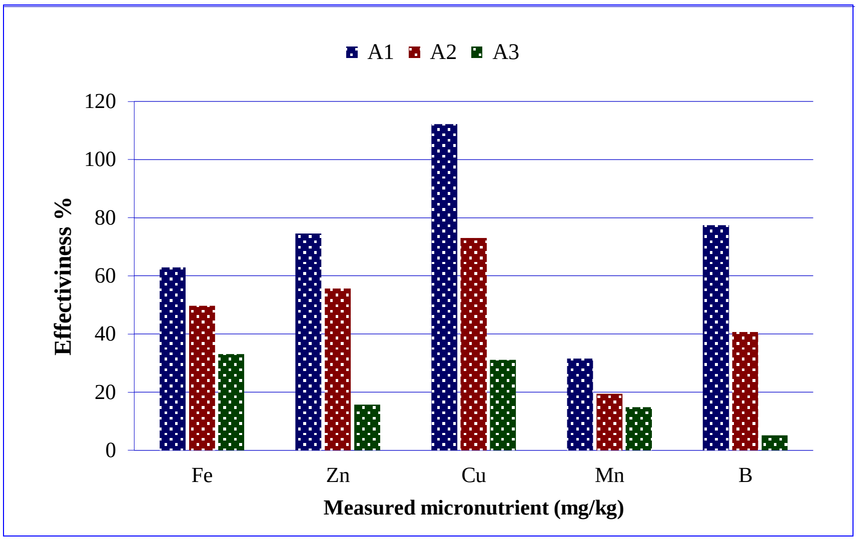

Figure (5):. Effectiveness % of different treatments of olive oil wastewater (OMW) micronutrient (mg/kg) of soil in which *Vicia faba* was cultivated.

but at lower rates compared to A_1. Specifically, A_2 showed percentage effect increases of (49.65%, 55.65%, 73.04%, 19.41%, and 40.65% for Fe, Zn, Cu, Mn, and B), respectively. A_3 demonstrated lower percentage effect increases, with values of (33.11%, 5.70%, 31.06%, 14.83%, and 5.16%) for Fe, Zn, Cu, Mn, and B, respectively. These findings indicate that A1 had the most significant impact on micronutrient levels in the soil among the treatments by an average percentage effect of (71.71%), followed by A_2 (47.68%) and A_3 (19.97%).

In Table (7) and Figure (6), treatment A_1 shows a notable increase in the levels of all tested micronutrients compared to the control (B). Particularly, treatment A_1 recorded a percentage effect increase of (56.00%, 80.14%, 100.87%, 54.00%, and 90.68%) for

Fe, Zn, Cu, Mn, and B, respectively. Treatment A_2 exhibited increases in micronutrient levels, albeit at slightly lower percentages compared to A_1. The perce-ntage effect increases for A_2 ranged from (33.90% to 74.40%) across the tested micronutrients. Similarly, treatment A_3 showcased improvements in micronu-trient levels, yet with the lowest percentage effect increase among the treatments, ranging from (21.92% to 36.20%). These findings indicate that A_1 had the most significant impact on micronutrient levels in the soil among the treatments by an average perce-ntage effect of (76.34%), followed by A_2 (45.55%) and A_3 (22.77%).

In Table (8) and Figure (7), the measured heavy metals were varied across different OMW treatments compared to control for both cultivated crops. Treatment A_1 exhibited an increase in the levels of heavy metals compared to the control (B), with the highest increase observed in Polyphenols, reaching (94.75%) compared to the con-trol. A_2 and A_3 also showed higher levels in these parameters, with percentage effects of (81.33%) and (55.44%) respectively for the overall heavy metal levels and polyphenols compared to the control. However, in Table (9) and Figure (8), treatment A_1 exhibited an increase in the levels of heavy metals compared to the control (B), with the highest increase observed in polyphenols, reaching (90.82%) compared to the control. A_2 and A_3 also recorded higher levels in these parameters, with percentage effects of 56.74% and 24.44%, respectively for the overall heavy metal levels and polyphenols compared to the control.

Table (7): Effects of olive mill wastewater (OMW) treatment applications on soil micronutrient levels in barely cultivation.

Treatment applied	Micronutrient measured (mg/kg)				
	Fe^{2+}	Zn^{2+}	Cu^{2+}	Mn^{2+}	B OH^{4-}
B	222 ^{d} ±6.56	36.10 ^{d} ±1.00	15 ^{d} ±0.22	90.26 ^{d} ±2.18	2.36 ^{d} ±0.13
A1	346.33 ^{a} ±3.21	65.03 ^{a} ±0.94	30.13 ^{a} ±1.60	139 ^{a} ±1.04	4.50 ^{a} ±0.09
A2	314 ^{b} ±3.61	50.50 ^{b} ±0.73	26.16 ^{b} ±1.23	124.66 ^{b} ±4.16	3.16 ^{b} ±0.05
A3	270.66 ^{c} ±3.06	41.06 ^{c} ±0.64	20.43 ^{c} ±1.23	114 ^{c} ±3.61	2.73 ^{c} ±0.13

†Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly (p≤0.05) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary trea tment; A3, Advanced treatment.

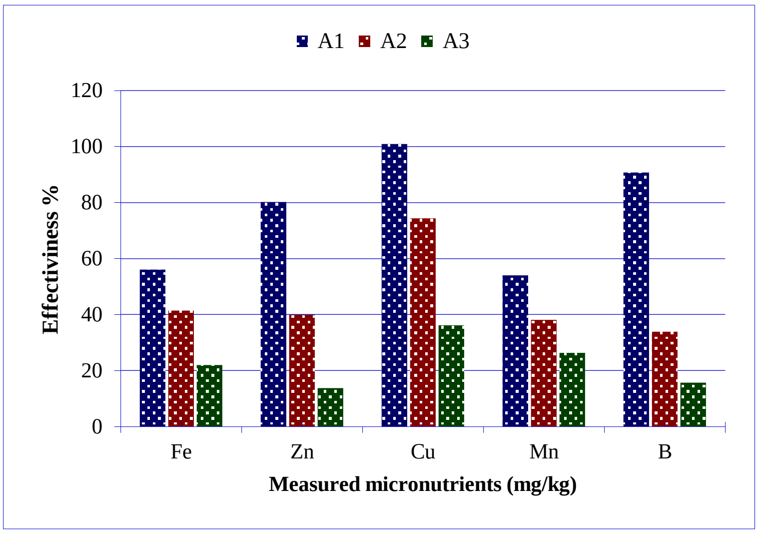

Figure (6): Effectiveness % of different treatments of olive oil wastewater (OMW) micronutrient (mg/kg) of soil in which barely was cultivated. A_1, Primary treatment; A_2, Secondary treatment; A_3, Advanced treatment.

Table (8). Effects of olive mill wastewater (OMW) treatment applications on soil heavy metals and total polyphenols levels in *Vicia faba* cultivation.

Treatment applied	Measured heavy metals (mg/kg)					Polyphenols (mg Kg^{-1})
	Pb	Cd	Ni	Co	Cr	
B	nd	Nd	nd	nd	nd	609.00 ^{d} ±5.57
A1	0.860 ^{a} ±0.05	0.506 ^{a} ±0.03	1.44 ^{a} ±0.06	2.57 ^{a} ±0.09	0.970 ^{a} ±0.02	1186.00 ^{a} ±3.61
A2	0.696 ^{b} ±0.01	0.400 ^{b} ±0.01	1.36 ^{b} ±0.03	2.36 ^{b} ±0.03	0.833 ^{b} ±0.02	1104.33 ^{b} ±3.21
A3	0.583 ^{c} ±0.02	0.326 ^{c} ±0.01	1.24 ^{c} ±0.04	2.23 ^{c} ±0.07	0.756 ^{c} ±0.01	946.66 ^{c} ±25.17

†Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly (p≤0.05) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

Table (9): Effects of olive mill wastewater (OMW) treatment applications on soil heavy metals and total polyphenols levels in barley cultivation.

Treatment applied	Measured heavy metals (mg kg^{-1})					Polyphenols (mg Kg^{-1})
	Pb	Cd	Ni	Co	Cr	
B	nd	nd	nd	nd	nd	356.00 ±8.19 ^{d}
A1	0.77 ^{a} ±0.02	0.40 ^{a} ±0.01	1.24 ^{a} ±0.03	2.03 ^{a} ±0.06	0.79 ^{a} ±0.02	679.33 ±15.72 ^{a}
A2	0.60 ^{b} ±0.01	0.31 ^{b} ±0.00	1.06 ^{b} ±0.02	1.79 ^{b} ±0.04	0.65 ^{b} ±0.01	558.00 ±6.33 ^{b}
A3	0.52 ^{c} ±0.03	0.28 ^{c} ±0.01	0.94 ^{c} ±0.05	1.47 ^{c} ±0.07	0.52 ^{c} ±0.02	443.00 ±5.39 ^{c}

[†]Data are means ± standard deviation. Means with same superscript letters, per column, are not significantly ($p \leq 0.05$) different based on Duncan Multiple Rang test. B, Control irrigation water; A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

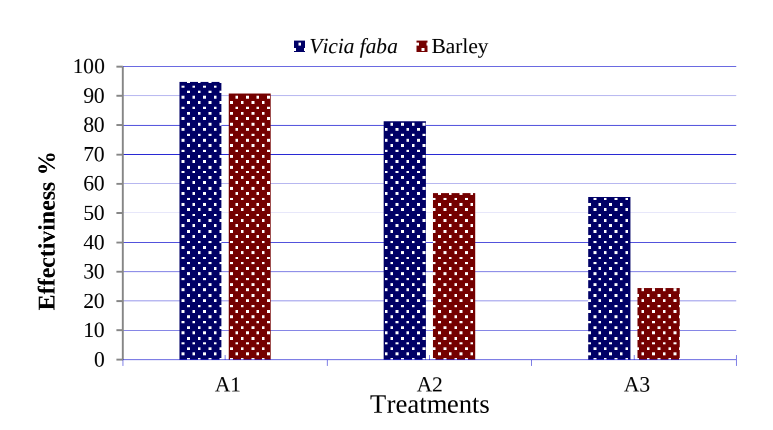

Figure (8): Effectiveness % of different treatments of olive oil wastewater (OMW) on polyphenol of soil in which *Vicia faba* and barely plants were cultivated. A1, Primary treatment; A2, Secondary treatment; A3, Advanced treatment.

DISCUSSTION

Throughout the study, the pH of the soil remained stable, while the electrical conductivity (EC) exhibited an initial decrease, followed by an increase and eventual decrease. In Tables 3 and 4, there was a consistent increase in values for organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K) across all treatments. Beans, in particular, showed a more substantial increase compared to barley. Treatment A_2 stood out, demonstrating a significant 25% improvement in most indicators.

In Tables (5 and 6), Cations such as calcium, magnesium, and sodium increased in the soil of both crops under treatments A_1 and A_2, with treatment A_2 achieving a better balance. Anions displayed an overall increase in all indicators. This aligns with findings from Sierra *et al*. (2007), Mechri *et al*. (2007, 2008), suggesting that soils in semi-arid areas benefit from the rich organic matter in olive mill wastewater (OMW), serving as a vital source of nutrients (N, P, K) for plants. Kapellakis *et al*. (2008) reported that the application of OMW did not cause significant problems on cultivated soil. Controlled application of 300L/m^2/h/y of OMW led to an increase in organic content, presenting an economic alternative for soil amendment compared to chemical fertilizers. Chartzoulakis *et al*. (2010) supported the study study, indicating increased potassium availability and enhanced soil fertility with OMW treatment.

Phenolic content showed a an increase, although it decomposed rapidly with no observed accumulation trend after subsequent applications. Mojiri (2011) indicated increased electrical conductivity, phosphorus, organic matter, total nitrogen, sodium, chloride, iron, cadmium, zinc, and a decrease in soil pH with wastewater irrigation.

Contrary to these findings, Barbera *et al.* (2013) suggested that OMW might not be suitable for heavy soils, potentially harming the structure of clay soils. DI Bene *et al*. (2013) emphasized intermittent OMW irrigation to mitigate potential impacts. Results of Mekki *et al*. (2013) aligned with the study, showing an increase in electrical conductivity, total organic carbon, and total nitrogen with untreated OMW suitable for soil fertilization. Treated OMW exhibited a slightly alkaline nature and richness in potassium, calcium, magnesium, and iron. Phenolic compounds were predominantly retained in the upper soil layers. Chartzoulakis *et al*. (2014) reported a similar direction, attributing the increase in soil nitrogen to the rise of nitrogen-fixing microflora. The cost of OMW application on soil was considered reasonable. Mehmood *et al* (2019) regarded heavy metals were consistent with the study. Chaari *et al*. (2015) demonstrated that the application of varying doses of OMW for nine successive years caused an increase in soil organic matter.

The study observed a gradual increase in potassium, nitrogen, and phosphorus with the OMW application rate. However, the increase in phenols was not proportional to the applied doses. Angelakis and Snyder (2015) demonstrated a significant reduction in both inorganic and organic constituents of OMW-applied wastewater, with notable removal percentages at a soil depth of 15 cm. However, Hossain *et al*. (2016) emphasized the crucial role of utilizing agricultural by-products in soil management to mitigate heavy metal toxicity, enhance soil porosity and aggregate stability, and reduce soil erosion and runoff. Complementing this, Balkhair and Ashraf (2016) highlighted the influence of various soil factors on the absorption and accumulation of heavy metals in plant tissues, identifying acidic soil conditions as a primary driver of heavy metal mobilization and subsequent uptake by plants. In a similar vein, Jaramillo and Restrepo (2017) linked alterations in soil pH to variables such as soil cover type, soil texture, and irrigation practices, which collectively influence nutrient and metal availability, cation exchange capacity (CEC), and the mineralization of organic matter. These authors further postulated that prolonged irrigation with wastewater can lead to detrimental changes in soil texture and increase heavy metal concentrations, which can act as limiting factors for overall soil fertility and plant health. Collectively, these studies underscore the complex interplay between soil properties, agricultural practices, and environmental factors in determining the fate and impact of heavy metals in agricultural systems. Meanwhile, a study done by Hussain *et al*. (2019) suggested the elevated levels of heavy metals in plant roots can emphasize the potential toxicity for human or animal consumption and recommending the discarding of such plants.

Recent results in Tables 3 and 4 aligned with Allalat *et al* (2023) indicating an increase in nitrogen, phosphorus, potassium, organic matter, electrical conductivity, and polyphenols. However, these parameters decreased with concentrations of OMW exceeding 400 m^3ha^{-1}. In Tables 5 and 6 findings were consistent with Magdich *et al*. (2020), showing proportional influences of OMW concentration and application frequency on electrical conductivity, organic matter, total nitrogen, and potassium contents in the soil's treated layer. The study concluded that OMW agronomic application is a suitable practice for better managing this effluent, with positive effects on olive oil production and quality. Results in Tables 5, 6,7 and 8 aligned with Mohawsh *et al*. (2020), finding no harmful effects of OMW application

for all application rates. OMW increased soil organic matter and nutrient contents, potentially reducing the need for chemical fertilizers. Results in Tables 3, 4, 5 and 6 were consistent with Halalsheh *et al*. (2021), reporting that composting OMW following a solar drying step could produce organic fertilizer with 57% organic carbon content and N, P, K contents of 3.5%, 1%, and 6.5%, respectively. The study suggested that recycling valuable nutrients and organic matter found in OMW through agricultural land application could be a feasible solution.

Recently, Halasheh *et al*. (2021) conducted studies in Jordan and reported no negative impacts observed in soil or plants irrigated by OMW. They highlighted that OMW is one of the most complex and difficult-to-treat wastewater types. While technological advances for OMW treatment exist, costs remain a limiting factor in scaling up, emphasizing the need to modify legislation for improved OMW management, especially in Jordan, to avoid discharges into wadis or disposal in public sewage networks.

CONCLUSION

The management of olive mill wastewater (OMW) is essential due to its significant environmental implications, particularly stemming from its high organic content and potential toxicity. This study investigated the effects of treated OMW on soil properties in a semi-arid region, comparing it with a control system irrigated with conventional farm water without fertilization. The application of treated OMW, subjectted to various physical and physiochemical treatment methods, demonstrated a positive impact on soil properties, enhancing essential nutrients necessary for the growth of *Vicia faba* (beans) and *Hordeum vulgare* (barley). In conclusion, the study provides strong support for the positive effects of OMW on some soil properties. Treatment A_2, in particular, demonstrated a balanced improvement across various indicators. These findings are consistent with previous research, indicating the potential economic viability of OMW as a soil amendment. Future research should focus on optimizing the utilization of OMW in agricultural systems, exploring its long-term effects on soil health, crop yield, and environmental sustainability while minimizing any potential adverse impacts.

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التقييم المتكامل لمياه الصرف الصحي لمعصرة الزيتون كتعديل مستدام للتربة: التأثيرات على بعض خصائص التربة في النظم الزراعية شبه القاحلة

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تهدف الدراسة إلي تقييم تأثير المعالجات الفيزيائية المختلفة على مياه صرف مصانع زيت الزيتون (OMW) وتأثيرها علي التربة، حيث تم جمع OMW من مصنع لزيت الزيتون بمدينة العريش بالقرب من جامعة العريش وتخزينها في خزان من الخرسانة غير المغطى. تم تنفيذ مراحل مختلفة من المعالجة بدءًا من المعالجة الأولية (الفيزيائية) لإزالة الجسيمات الكبيرة والعائمة، ومروراً بالمعالجة الثانوية (الفيزيوكيميائية) لإزالة المواد العضوية المذابة، وصولاً إلى المعالجة المتقدمة باستخدام الكربون النشط.تمت متابعة تأثيير الري بالمياه المعالجة لصرف مصانع زيت الزيتون على الصفات الفيزيائية والفيزيوكيميائية للتربة، بما في ذلك الحموضة، التوصيل الكهربائي، مستويات العناصر الكبرى والصغرى والمعادن الثقيلة والبوليفينولات في التربة ومقارنتها بتأثير مياه الري الموجودة بالمزرعة أظهرت النتائج أن استخدام مياه صرف مصانع زيت الزيتون قد أدى إلى زيادة في بعض العناصر الغذائية والمغذيات في التربة، مع تحسين في خصائص التربة. كما تبين أن المعالجة الثانوية (A_2) كان لها تأثير متوازن أفضل على المؤشرات المختلفة. تتفق هذه النتائج مع العديد من الدراسات السابقة التي أظهرت فوائد استخدام مياه صرف مصانع زيت الزيتون على التربة والنباتات. يمكن القول إن هذه الدراسة تشير الي إمكانية استخدام مياه صرف مصانع زيت الزيتون كوسيلة اقتصادية وبيئية لتحسين صفات التربة وزيادة الإنتاج الزراعي.