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Article

Enhancing Sustainable Olive Tree Productivity Through Bio-Amended Composted Olive Mill Pomace

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Abstract: An integration of olive waste management and their cultivation with integrated circular economy principles to enhance productivity and minimize environmental burdens. This study examines the composting of olive mill pomace, enriched with biological amendments as vermiwash, the fungal consortium of *Phanerochaete chrysosporium* and *Trichoderma* sp., with farmyard manure for improving soil fertility, enhancing olive tree growth, and promoting productivity. The compost was prepared in June 2021 and divided into three piles as follows: pile 1 (olive mill pomace + olive leaves + farmyard manure), pile 2 (olive mill pomace + olive leaves + farmyard manure + vermiwash), and pile 3 (olive mill pomace + olive leaves + farmyard manure + fungal consortium). Each pile received urea (0.25%) and rock phosphate (3%) as a nutrient amendment. The composting process was monitored through temperature profiles, pH, electrical conductivity, and organic matter decomposition, highlighting the efficacy of bioagents in achieving thermophilic conditions, nutrient stabilization, and compost maturity. The prepared compost piles were added in December to Dolce olive trees at 15 years and compared with the usual farm compost (as a control) to assess their impacts on olive tree vegetative growth, leaf nutritional status, flowering, fruit set, fruit characteristics, yield, oil content, and soil fertility during two growing seasons (2022 and 2023). Results demonstrate the superior performance of fungal-enriched compost (olive mill pomace + olive leaves + farmyard manure + fungal consortium) in enhancing soil health, nutrient availability, olive yield, and net profit, supporting its application in sustainable agriculture. The trial's findings indicate that using converted olive wastes is essential for enhancing the nutritional status and soil fertility of the trees, thereby increasing fruit output and quality, productivity, and net income. lowering the amount of fertilizer and the environmental pollution caused by these wastes.

Key words: Olive Mill Pomace; Bio-Amended Compost; Lignocellulosic fungi; Vermiwash; Olive Productivity.

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1. Introduction

Sustainable olive cultivation and processing, based on a circular economy, considers the aims of socio-economic enhancement along with environmental burdens minimized within olive plantations of the Mediterranean region **(Velasco-Muñoz *et al.*, 2022)**. Such aims integrate many principles and practices into olive tree cultivation, such as soil management through bio-organic-based amendments, including composts, to improve soil fertility and structure and transition to organic farming practices by reducing agrochemical inputs **(Fernandez *et al.*, 2013).** Composting olive residues/wastes potentially offer an efficacious and ecologically advantageous approach to recycling such materials by producing a valuable resource using best practices and adjusting techniques based on specific conditions **(Magdich *et al.*, 2022)**. Biologically, vermiwash and fungal consortia like *Phanerochaete* sp. and *Trichoderma* sp. offer distinct benefits for organic waste composting and soil health **(Pathma and Sakthivel, 2012)**. Vermiwash, a liquid extract produced from vermicomposting, is rich in enzymes, plant growth hormones, and beneficial microbes, which enhance nutrient uptake and promote plant growth when used as a foliar spray or soil drench. On the other hand, the consortium of *Phanerochaete* and *Trichoderma* fungi actively degrades lignin and complex organic matter, accelerating the breakdown of recalcitrant materials like olive mill pomace. *Phanerochaete* is known as a model white rot fungus specializes in the degradation of abundant aromatic polymer lignin while leaving the white cellulose nearly untouched **(Baldrian and Valaskova, 2008).** Meanwhile, *Trichoderma* is known as cellulolytic as well as for its biocontrol properties and ability to promote plant resistance against pathogens **(Harman *et al.*, 2004)**. Both approaches are valuable in sustainable agriculture, with vermiwash emphasizing plant growth and microbial balance, while fungal consortia focus on efficient composting and pathogen suppression. The current study searches for potential processing of olive mill pomace with three biological agents to produce compost to be applied as organic fertilizer on olive tree cultivation.

2. Materials and Methods

A- Composting of OMP

Olive Mill Pomace (OMP) as a primary material

Olive mill pomace (OMP), a byproduct of the two-phase olive oil extraction process kindly supplied by the Food Technology Research Institute, Agriculture Research center, Egypt, was utilized as the primary organic material for composting. This waste material consists of a mixture of olive pulp, skin, pits, and residual oil, rich in organic matter and phenolic compounds. Due to its high moisture content and nutrient profile, OMP provides an excellent base for composting but requires amendment with bulking agents like olive leaves to improve aeration and reduce compaction. The OMP used in this study was freshly collected from a local olive mill, stored in shaded conditions, and incorporated into the composting process within six months of production. The main characters of used OMP are represented in Table (1).

Olive leaves as a bulking agent

Olive leaves (OL) sourced from the Food Technology Research Institute were used as a bulking agent in the composting process of olive mill pomace. Due to their fibrous structure and high lignocellulosic content, olive leaves are ideal for improving the physical properties of the compost mixture. Their role as a bulking agent is to enhance aeration, facilitate water drainage, and create a balanced carbon-to-nitrogen ratio, essential for optimizing microbial activity during composting. Data of Table (2) represents features of used olive leaves.

Farmyard manure as bio- and bulking agent

Farmyard manure (FM), consisting of a mixture of animal dung and bedding materials, was used as an amendment during the composting process. Rich in nitrogen, microbial populations, and organic matter, FM helps accelerate the decomposition of organic materials such as olive mill pomace by enhancing microbial activity and balancing the carbon-to-nitrogen (C/N) ratio. The manure was sourced from a local farm, air-dried to reduce excess moisture, and evenly incorporated into the compost pile. Table (3) outlines key characteristics of farmyard manure.

Table (1). Properties of olive mill pomace (OMP) used as a primary material during composting

Parameter	Value	Unit
Density	0.84 ± 0.12	g/cm³
Moisture Content	55.66 ± 11.83	%
pH (OMP water suspension 1: 5)	4.55 ± 0.41	-
EC (OMP water extract 1: 10)	3.08 ± 0.82	dS/m
Ash Content	4.25 ± 1.87	%
Nitrogen (N)	1.21 ± 0.51	%
Phosphorus (P)	0.18 ± 0.07	%
Potassium (K)	1.03 ± 0.17	%
Organic Carbon	49.73 ± 3.95	%
Organic Matter	85.73 ± 6.81	%
C/N Ratio	47.62 ± 19.46	-
Total Phenolic Compounds	4 ± 0.83	g/kg
Lignin	17.48 ± 1.83	%
Cellulose	4.41 ± 1.02	%
Biological Activity (mg CO_2/kg)	182.47 ± 98.55	mg CO_2/kg dry matter/day

Table (2). Properties of olive leaves used as a bulking agent during composting

Parameters	Values	Units
Density	0.22±0.03	g/cm³
Moisture Content	13.11±0.81	% Fresh weight
Ash content	19.15±3.06	dS/m
Nitrogen (N)	1.2±0.14	%
Phosphorus (P)	0.13±0.02	%
Potassium (K)	1.08±0.08	%
Organic Carbon	46.9±1.77	%
Organic matter	80.86±3.06	%
C/N Ratio	39.55±3.22	--

Table (3). Key characteristics of farmyard manure used as an amendment during composting

Parameters	Values	Units
Moisture Content	70.47±4.17	%
pH (farmyard manure water suspension 1:5)	7.29±0.55	-
EC (dS/m at 25ºC) (farmyard manure water extract 1:10)	3.84±0.54	dS/m
ASH	35.77±3.45	%
Total Nitrogen (N)	1.74±0.21	%
Total Phosphorus (P)	0.4±0.08	%
Total Potassium (K)	1.21±0.26	%
Organic Carbon	37.27±2	%
Organic matter	64.24±3.45	%
C/N Ratio	21.8±3.67	-

Fungal Consortium as a bio-agent

A fungal consortium of *Phanerochaete chrysosporium* and *Trichoderma* sp. was employed as a bioagent to enhance the composting of olive mill pomace. These fungi, known for their efficient lignocellulosic degradation, were kindly supplied by the Microbiol. Res. Dept, Soil, Water, and Env. Res. Ins. (SWERI), ARC, Egypt. The fungal strains were cultured using Corn Steep Liquor (CSL) as the primary medium, an industrial by product of corn wet milling by The Egyptian Starch and Glucose Company (ESGC), Cairo, Egypt. Using CSL the main ingredient provides an economical, nutrient-rich environment conducive to fungal growth and enzyme production, particularly for ligninolytic and cellulolytic enzymes **(Liggett and Koffler, 1948**). The medium was prepared according to **Schroeder (1966), and Akhtar *et al.*, (1997)** by diluting CSL to a 1% (v/v) concentration in tap water and supplemented with glucose (10 g/L), $MgSO_4 \cdot 7H_2O$ (1 g/L), KH_2PO_4 (1 g/L), and yeast (0.5 g/L) to further enhance fungal growth. The pH was adjusted to 6.0 using sodium hydroxide. The medium was autoclaved at 121°C for 15 minutes to ensure sterility before inoculation. The fungal consortium was incubated at 28°C for 5–7 days, allowing for active mycelial growth.

Vermiwash as a bio-agent

Vermiwash, a nutrient-rich liquid collected from the drainage of vermiculture beds of vermicomposting systems processed by the Central Laboratory of Organic Agriculture (CLOA), ARC, Egypt, was applied as a bio-enhancer amendment in the composting of OMP. In this study, freshly harvested vermiwash was diluted at a 1:10 ratio and sprayed periodically over the compost mixture to ensure even microbial distribution. The following parameters in Table 4 characterized Vermiwash used in this study.

Table (4). Key characteristics of Vermiwash used as amendment agent during composting

Parameter	Value	Unit	Parameter	Value	Unit
pH	7.01±0.16	-	Bacteria	4.7×10^7	CFU/mL
Electrical Conductivity	1.61±0.31	dS/m	Fungi	5.9×10^4	CFU/mL
Total Nitrogen (N)	177.31±21.62	mg/L	Nitrogen-fixing Bacteria	5.6×10^5	CFU/mL
Avaliable Phosphorus (P)	41.03±7.11	mg/L	Phosphate-solubilizing Bacteria	5.9×10^4	CFU/mL
Avaliable Potassium (K)	125.51±19.81	mg/L	Phytohormones*	7.38±1.97	ppm
Organic Carbon	248.81±42.03	mg/L	Enzymes (Protease, Amylase, etc.)	66.93±10.3	IU/mL

*Auxins were measured using the Salkowski reagent method

Composting Process and Experimental Setup

The composting process was designed to evaluate the efficacy of the mixture of olive mill pomace (OMP) as the primary substrate, olive leaves (OL) and farmyard manure (FM) as a bulking agent to compare amendments of bioagents, namely, (FM) *vs* vermiwash (VW) *vs* a fungal consortium (FC) including *Ph. chrysosporium* and *Tri.* species. The experimental setup involved the preparation of compost piles, monitoring key environmental parameters, and assessing microbial, chemical, and physical changes throughout the composting period.

Compost Formulation

The OMP was used as the base component of the compost mixture as the primary material, supplemented by olive leaves (OL), farmyard manure (FM) as bulking agents, and urea (46% N) along with rock phosphate (22.5% P_2O_2) as a nutrient amendment at a rate of 0.25 and 3%, respectively. The dry weights of each material were calculated by accounting for the moisture content. The C/N ratio for the mixture was determined according to **Trautmann and Krasny (1997)** using the following equation:

$$ {}^{C}\!/_{N} = \frac{(W_{MOP}\ X\ C_{OMP}) + (W_{OL}\ X\ C_{OL}) + (W_{FM}\ X\ C_{FM})}{(W_{MOP}\ X\ N_{OMP}) + (W_{OL}\ X\ N_{OL}) + (W_{FM}\ X\ N_{FM})} $$

where:

W_{OMP}, W_{OL}, W_{FM} represent the dry weights of olive mill pomace, olive leaves, and farmyard manure, respectively.

C_{OMP}, C_{OL}, C_{FM} represent the carbon content percentages.

N_{OMP}, N_{OL}, N_{FM} represent the nitrogen content percentages.

Based on this equation, the optimal proportions of OMP (200 kg), OL (15 kg), and FM (60 kg), were calculated to maintain a C/N ratio of 35. Overall, in the composting process, the moisture content of the compost piles was potentially maintained between 50-60% using the “squeeze hand” method.

The following treatments were prepared:

- **T1 (Pile-1):** OMP + OL+ FM + U + RP**.**
- **T2 (Pile-2):** OMP + OL+FM + U + RP + VW ~ 4.5 liters/ton for spraying**.**
- **T3 (Pile-3):** OMP + OL+FM + U + RP + FC ~10 liters/ton (direct inoculation)**.**

Where:

OMP (Olive Mill Pomace); OL (Olive Leaves); FM (Farmyard Manure); U (Urea); RP (Rock Phosphate; VW (Vermiwash); and FC (Fungal consortium).

Composting Conditions

The composting process was conducted outdoors under natural conditions in the June 2021 season. Each pile was 1.5 m X 1.5 m X 1.0 m to ensure sufficient aeration and microbial activity. The moisture content of each pile was maintained at 55-60% using a hand squeeze test throughout the composting process, adjusted by regular turning and watering.

Key Parameters for Composting Process Assessment

The temperature was monitored throughout the process over 90 days, though measurements were taken at five positions—L1 (left side at 20 cm), L2 (left side at 80 cm), Core (middle at 40 cm), R1 (right side at 20 cm), and R2 (right side at 80 cm). Samples were taken at 0, 15, 30, 45, 60, 75 and 90 days for chemical and microbial analysis monitoring through several key parameters that are indicative of decomposition. The pH and electrical conductivity (EC) were measured using a 1:10 (w/v) compost-water suspension compost-to-water ratio as recommended by **Trautmann and krasny (1997)**. Chemical assay of samples during composting performed based on methods of **Page (1982).**

Microbial activity, which indicates stability, was assessed by measuring dehydrogenase activity and CO_2 evolution. Dehydrogenase activity reflects the overall microbial oxidative activity was determined using the method described by **Casida *et al.* (1964).** On the other hand, CO_2 evolution was measured as an indicator of microbial respiration and organic matter mineralization using the method outlined by **Trautmann and krasny (1997).**

Germination index (GI) was used in phytotoxicity assay to evaluate compost maturity and its suitability for use as an organic fertilizer. These tests involved using seeds of Lepidium sativum (cress) and compost extracts to determine germination percentage and root elongation, following the method described by **(Trautmann and krasny, 1997).**

B- Olive tree orchard experimentation

Trial location and plant material

The agronomic experiment on (15-years-old) olive tree Dolce cultivar was carried out during two seasons (2022 and 2023) at a Private Farm located 64 kilometers distant from Cairo (Cairo-Alexandria Desert Road), Egypt (30˚268` 215‶) N Latitude, (30˚806` 534`) E Longitude. To investigate the effect of the outcome composts (T1, T2, and T3) against the control or the farm’s compost (T) as a usual one of the farm and studying their effect on vegetative growth, flowering, mineral content in leaves, fruit properties, yield, and oil content. The trees were grown in sandy soil 5*5 meters apart (168 trees/fed) under a drip irrigation system (2400 m^3/fed). The chosen trees were nearly uniform in shape and size and free from pathological and physiological disorders.

The trial is a comparative study of three prepared composts with usual farm compost as follows:

- **T:** usual farm compost **(control).**
- **T1:** OMP + OL + FM
- **T2:** OMP + OL + FM + VW
- **T3:** OMP + OL + FM + FC

The experiment followed a complete randomized block design_with 3 trees (replicates)/plot; for each tree, the trees received the same cultural management (irrigation, weed, pest, and disease control usually applied in the orchard except for the fertilization treatments). The compost was mixed with the surface soil under the tree at a rate of 25 kg/tree/year during soil preparation in December of both seasons.

The criteria of soil, applied composts, and irrigation water in (Tables 5, 6, and 7) were assayed based on procedures and methods of **Black (1965), Page (1982) and Eaton (1999).**

Table (5). Physicochemical properties of farm's soil

<table>
<tr><th colspan="11">Soil mechanical analysis (%)</th></tr>
<tr><th colspan="4" rowspan="3">Particle size distribution (%)</th><td colspan="2">Sand</td><td colspan="2">60.47</td><th colspan="2" rowspan="3">Textural grade</th><th rowspan="3">Sandy clay loam</th></tr>
<tr><td colspan="2">Silt</td><td colspan="2">14.69</td></tr>
<tr><td colspan="2">Clay</td><td colspan="2">24.84</td></tr>
<tr><th colspan="11">Soil chemical properties</th></tr>
<tr><th rowspan="2">pH
(soil paste extract)</th><th rowspan="2">E.C.
dS m^{-1}
(25ºC)</th><th rowspan="2">$CaCO_3$
(%)</th><th colspan="4">Soluble cations* (meq/ L)</th><th colspan="4">Soluble anions* (meq/L)</th></tr>
<tr><th>Ca^{++}</th><th>Mg^{++}</th><th>Na^+</th><th>K^+</th><th>$CO_3^=$</th><th>HCO_3^-</th><th>$Cl^–$</th><th>$SO_4^=$</th></tr>
<tr><td>7.86</td><td>5.15</td><td>3.02</td><td>20.1</td><td>7.1</td><td>21.2</td><td>2.6</td><td>--</td><td>2.67</td><td>40.02</td><td>8.31</td></tr>
<tr><th colspan="2" rowspan="2">Organic matter (%)</th><th colspan="4">Available nutrients mg kg^{-1}</th><th colspan="5">DTPA-extractable mg kg^{-1}</th></tr>
<tr><th>N</th><th colspan="2">P</th><th>K</th><th colspan="2">Fe</th><th>Mn</th><th colspan="2">Zn</th></tr>
<tr><td colspan="2">0.21</td><td>1.28</td><td colspan="2">3.5</td><td>73.2</td><td colspan="2">1.14</td><td>1.24</td><td colspan="2">0.51</td></tr>
</table>

***** DTPA: Di-ethylene tri-amine penta-acetic acid.

Table (6). Key characteristics of applied composts

Compost properties	Treatments			
	T (control)	T1	T2	T3
pH (Compost water suspension 1: 5)	7.16	6.13	6.62	6.39
EC (dS/m at 25ºC) (Compat water extract 1: 10)	6.09	5.98	5.85	6.52
Organic matter (%)	30.80	32.41	30.21	29.52
C/N Ratio	18.27	15.19	12.11	11.12
Total-N %	0.98	1.24	1.41	1.54
Total-P %	0.81	0.96	1.00	1.15
Total-K %	1.27	0.97	1.19	1.12
CO_2-C/g OC/day	18.72	20.18	11.58	12.87
DHA (µg TPF/g/h)	7.91	4.75	9.07	10.46
Germination Index	0.94	0.89	0.92	0.96

T = control; T1 = (OMP + OL + FM) compost; T2: (OMP + OL+ FM + VW) compost & T3: (OMP + OL+ FM + FC) compost.

Table (7). Chemical analysis of well's water

E.C.w	**TSS**	**PH**	**Cations (meq/L)**				**Anions (meq/L)**			
mmhos	**ppm**									
			Mg^{++}	**Ca^{++}**	**K^{+}**	**Na^{+}**	**$SO_4^{=}$**	**Cl**	**HCO_3**	**CO**
0.84	537.6	7.4	2	4	0.2	2.1	0.2	6.1	2	00

The agronomical performance of different composts on soils was examined in both seasons using the following characteristics:

1. Vegetative growth parameters

Samples of approximately 30 adult leaves were taken from the middle position of selected shoots from each replicate tree in July of both seasons to determine shoot length averages (cm) and average leaf surface area (cm^2) according to **Ahmed and Morsy (1999).**

2. Leaf nutritional status

The leaf samples were taken from the middle position of shoots from each replicate tree in July of both seasons and washed, oven-dried at 70 °C till constant weight, and ground into a fine powder to determine the contents of nitrogen, potassium, and phosphorus (gm/100 g D.W.) in digested solution according to the procedures of **Motsara and Roy (2008).**

3. Flowering parameters

- Inflorescence length (the length of the axis of thirty inflorescences, taken randomly from each replicate, was measured in cm).
- Flowering density recorded as an average number of inflorescences per shoot and calculated per meter.
- The sex ratio (%) presented as a percentage of perfect flowers to the total number of flowers was calculated in previously thirty inflorescences for each replicate according to **Rallo and Fernandez-Escobar (1985).**

4. Fruit set, yield/tree, and fruit oil content

The olive harvest was carried out at the ripe stage (the end of October) to record the fruit set on each replicate tree after 21 days from full bloom, according to **Rallo and Fernandez-Escobar (1985)**, and their percentages of the number of fruits on each of the selected shoots were calculated. Also, average fruit yield (kg) per tree was determined for each treatment.

Oil content (%) in ripe fruit was determined by the Soxhlet fat extraction apparatus **(A.O.A.C., 2010).**

5. Fruit characteristics

The physical parameters of thirty fresh fruits randomly picked at harvest from each of the applied composts were characterized in the context of the following:

a) Average fruit length (cm), diameter (cm), and weight (g).

b) Average pit length (cm), diameter (cm), and weight (g).

c) Average flesh/fruit (%) = average flesh weight/average fruit weight x 100 (The average flesh weight presented as the average fruit weight subtracted from the average pit weight).

6. Soil characteristics

Soil samples were randomly collected at a depth of 60 cm from the zone of the end of root ramification of the canopy at the end of October 2022 and 2023, respectively, and the average of both seasons was determined. The soil criteria were evaluated using **Page, (1982)** protocols and techniques.

C- Economic evaluation

The economic evaluation based on the attached file for Egypt during 2022 and 2023 was computed according to **Coutu *et al.* (1961)** as follows:

- Total cost/fed/year (EGP) = fixed cost + compost cost

- Fixed cost/fed. = (mineral fertilization, labor, pesticides, etc.) =25000 L.E

- Compost cost/fed. = number of tree/fed × compost/tree (kg) × compost price/EGP/ton

(estimated compost prices: 500, 900, 920 and 980 EGP/ton for T, T1, T2, T3, respectively)

- Total income/treatment/fed (EGP) = (average yield of two seasons/fed (kg)/1000) × total price/ton (20000 L.E)

- Net profit = total cost – total income

D- Statistical analysis

The acquired data, which represent the average of three repetitions, were analyzed using the ANOVA method, in accordance with **Snedecor and Cochran (1980).** As stated by SAS, Duncan's multiple range tests were used to compare the mean differences at a 5% level **(SAS, 1986).**

3. Results and Discussions

A- Composting of OMP

Temperature profile

The box plot Figure 1, demonstrates typical thermophilic composting behavior with distinct gradients between the core and surface layer as indicative of varying composting activity and maturity.

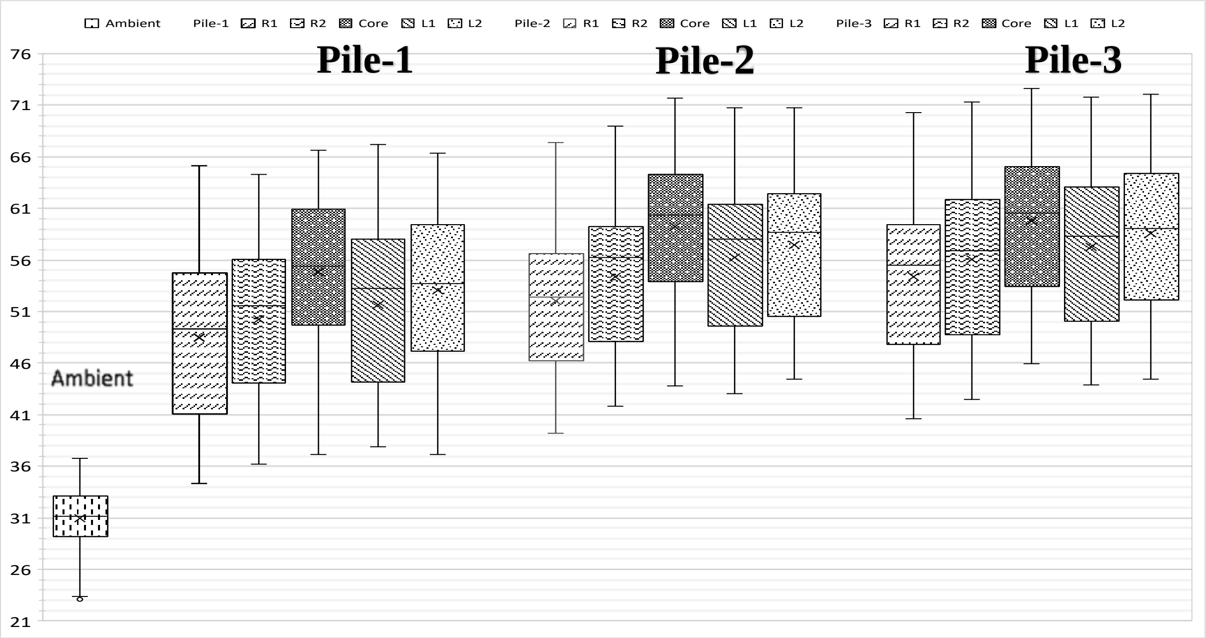

Figure (1). Temperature profile of three compost piles at different depths—surface: left (L1: 20 cm, L2: 80 cm), core (40 cm), and right (R1: 20 cm, R2: 80 cm)

In all piles, core temperatures consistently reached thermophilic levels (55–65°C), with Pile-3 (fungal inoculant) slightly outperforming the others in maintaining higher temperatures across multiple depths (L1, L2, R1, and R2), potentially due to the enhanced enzymatic activity provided by fungi like

Ph. chrysosporium and *Trichoderma sp.*, which are known for their lignocellulose-degrading capabilities (**Vargas-Garcia *et al.*, 2007, and Yang *et al.*, 2022)**. The core temperatures in all piles suggest sufficient microbial activity for effective organic matter breakdown, which is critical for compost stability and pathogen reduction **(Agnolucci *et al.*, 2013 and Ntougias *et al.*, 2013)**. Pile-1 and Pile-2 exhibited similar temperature trends, indicating that both farmyard manure and vermiwash supported active microbial communities capable of sustaining high temperatures necessary for the thermophilic phase. However, surface measurements in L1 and L2 showed lower temperatures than the core across all piles due to heat dissipation, typical of composting systems (**Themelis, 2005**). The fungal inoculant in Pile-3, however, exhibited a more even temperature distribution, suggesting that the inoculant may enhance microbial activity and heat retention at different composting depths, aligning with findings that fungi can boost organic matter decomposition **(Yang *et al.*, 2022).** Overall, the observed temperature profiles indicate that all three bioagents—farmyard manure, vermiwash, and fungal inoculant—were effective in maintaining optimal conditions for thermophilic composting. This sustained microbial activity across the thermophilic phase aligns with previous studies that emphasize the importance of temperature for efficient composting and nutrient cycling, validating the suitability of these bio agents for olive pomace composting **(Agnolucci *et al.*, 2013 and Ntougias *et al.*, 2013).**

pH and electrical conductivity

The pH and electrical conductivity (EC) trends in the three compost piles demonstrate typical fluctuations observed during organic matter decomposition.

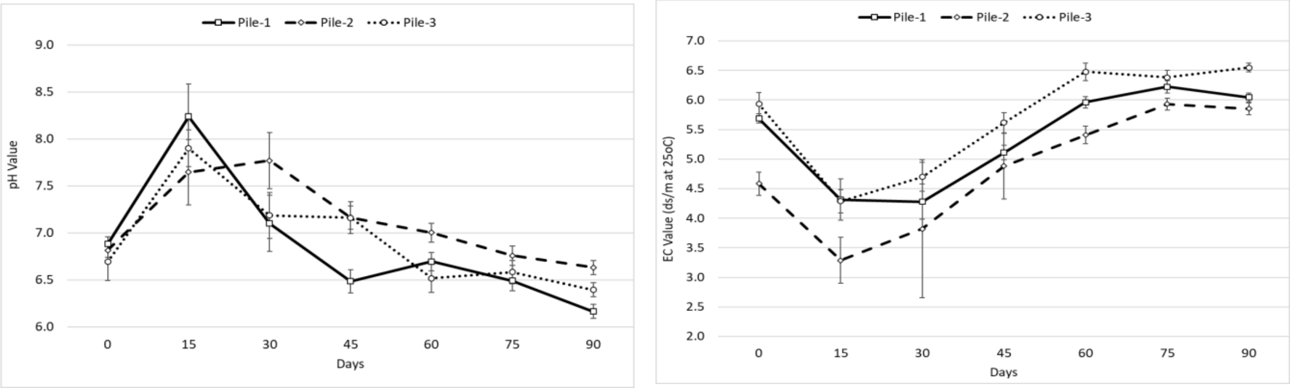

Figure (2). Changes in pH and EC in three composting piles over 90 days

The initial pH values in all piles were near-neutral, followed by a rise due to the release of ammonium compounds during the thermophilic phase **(Leone *et al.*, 2021**). As composting progressed, pH decreased and stabilized between 6.5 and 7.0, indicating a mature compost. Pile-3, treated with fungal inoculants, showed a slightly faster pH stabilization, likely due to the accelerated breakdown of lignin and cellulose by fungi.

The initial EC values varied among the piles, with Pile-3 showing the highest due to potential salt or nutrient residues from the inoculant. EC values initially decreased and then increased as organic matter decomposed and soluble salts were released. Pile-3 consistently exhibited the highest EC values, potentially due to the 0accelerated breakdown of organic matter by fungal activity **(Leone *et al.*, 2021).** While higher EC values can indicate nutrient availability, excessive salinity could negatively impact plant growth. Therefore, the choice of bio agent should consider the intended application of the compost to manage salinity levels effectively.

Organic matter degradation dynamics

The degradation of organic matter (Figure (**3**) content (OM) in all three piles over 90 days decreased significantly, with the most pronounced reduction observed in Pile-3 (Fungal Inoculants), followed by Pile-2 (Vermiwash), and Pile-1 (Farmyard Manure).

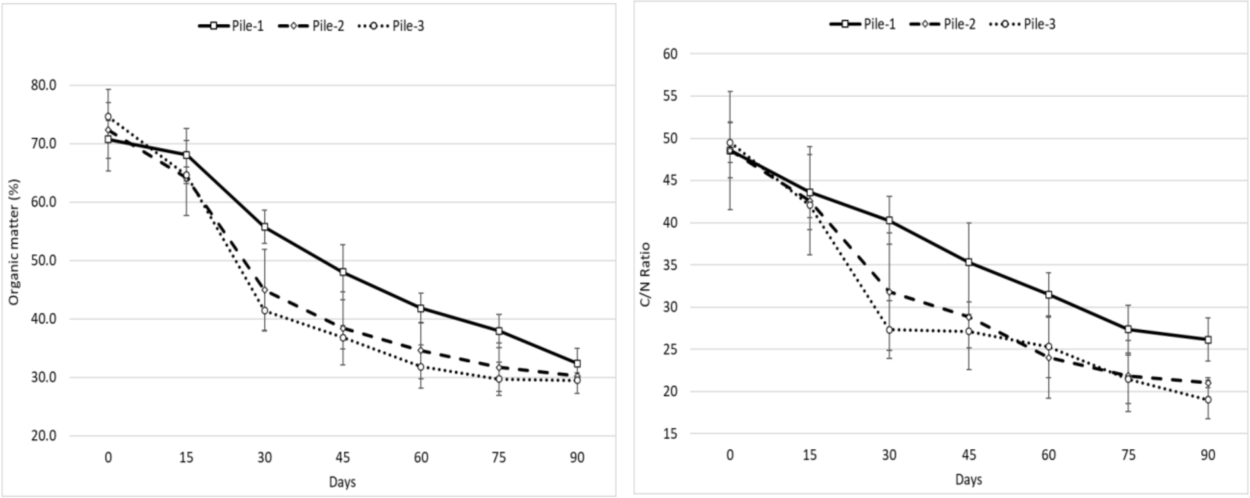

Figure (3). Changes in organic matter in three composting piles over 90 days.

Pile-3's enhanced degradation suggests the effectiveness of fungal bioagents in breaking down lignocellulosic compounds, consistent with their known enzymatic activity **(Agnolucci *et al.*, 2013, and Nemet *et al.*, 2021)**. The reduction in OM was accompanied by a corresponding decline in the C/N ratio, a critical parameter for compost maturity **(El-Tahlawy, 2014**). All piles exhibited initial C/N ratios above 45, indicative of carbon-rich materials. By day 90, the C/N ratios dropped below 25, with Pile-3 achieving the lowest values, followed by Pile-2 and Pile-1. This trend reflects the mineralization of carbon into CO_2 and microbial immobilization of nitrogen. The lower final C/N ratios (< 25) confirm the stabilization of organic matter and the maturity of the compost, aligning with criteria for high-quality compost suitable for agricultural use **(Thomson *et al.*, 2022, and Aylaj &Adani, 2023)**. These findings highlight the potential of bioaugmentation in enhancing compost quality and efficiency, particularly when managing complex organic residues like olive mill pomace **(Gómez-Muñoz et al., 2012, and Agnolucci *et al.*, 2013)**.

Agro-nutrients

Figure 4 of some agro-nutrient (N, P, and K) dynamics during the composting process of OMP with OL and different biological agents, it revealed a distinct fluctuation over a 90-day period as well as significant variations in total nitrogen (N), phosphorus (P), and potassium (K) content. The data indicated a progressive nutrient transformation, with T2 and T3 showing more pronounced improvements compared to the control treatment. Notably, the total nitrogen percentage exhibited a dynamic pattern, with initial increases followed by stabilization, which aligns with previous research on organic waste composting **(Manu *et al.*, 2021).** The vermiwash treatment (T2) and fungal consortium treatment (T3) demonstrated enhanced nutrient mineralization, potentially attributed to the bioactive agents' ability to accelerate decomposition and nutrient release**(Zhao *et al.*, 2022).** The fungal consortium, comprising *Ph. chrysosporium* and *Trichoderma* sp., likely contributed to more efficient organic matter breakdown and nutrient solubilization **(El-Tahlawy, 2014)**. Phosphorus and potassium percentages also showed interesting transformations throughout the composting process, with gradual changes reflecting the complex microbial interactions and nutrient cycling mechanisms **(Haouas *et al.*, 2021)**. The biological treatments (T2 and T3) consistently outperformed the control treatment, suggesting that targeted biological interventions can significantly improve the nutrient quality of olive mill waste compost.

These findings underscore the potential of innovative composting strategies in transforming agricultural waste into valuable organic fertilizers, supporting sustainable waste management and circular economy principles **(Morrissey and Browne, 2004**). The study highlights the importance of selecting appropriate biological agents to enhance nutrient dynamics and overall compost quality.

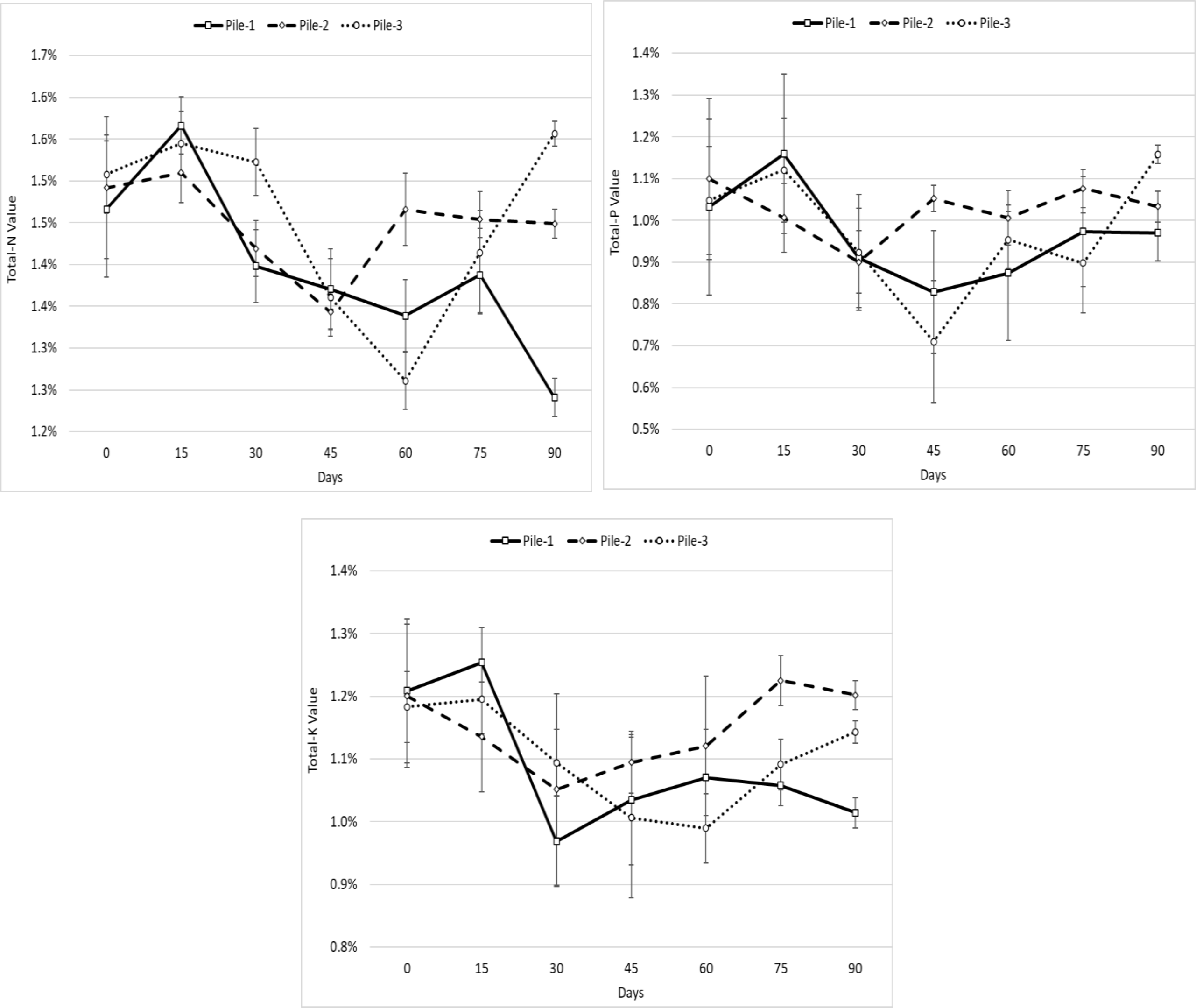

Figure (4). Changes in total nitrogen, phosphorus, and potassium (NPK) percentages in three composting piles over 90 days

Biological activity

The composting process over 90 days (Figure 5) revealed dynamic changes in carbon dioxide (CO_2) emissions, dehydrogenase activity (DHA), and germination index (GI). The three treatments showing increased CO_2 production rates compared to the control treatment, indicating enhanced microbial activity and organic matter decomposition **(Nemet *et al.*, 2021)**. The DHA values, which reflect microbial oxidative activity, were significantly higher in T2 and T3, suggesting that the biological agents stimulated microbial growth and metabolism **(Barrena *et al.*, 2008).** The CO_2-C emissions, a proxy for microbial activity, were higher in T2 and T3, indicating accelerated organic matter breakdown **(Thomson *et al.*, 2022**). The GI, a measure of compost phytotoxicity, showed a gradual boosting in all treatments after passing decline, indicating a depletion in phytotoxic compounds and an improvement in compost maturity **(Aylaj and Adani, 2023**). The results demonstrate that the addition of vermiwash and fungal consortium as bioagents can accelerate the composting process, enhance microbial activity, and improve compost quality, supporting the development of sustainable waste management strategies.

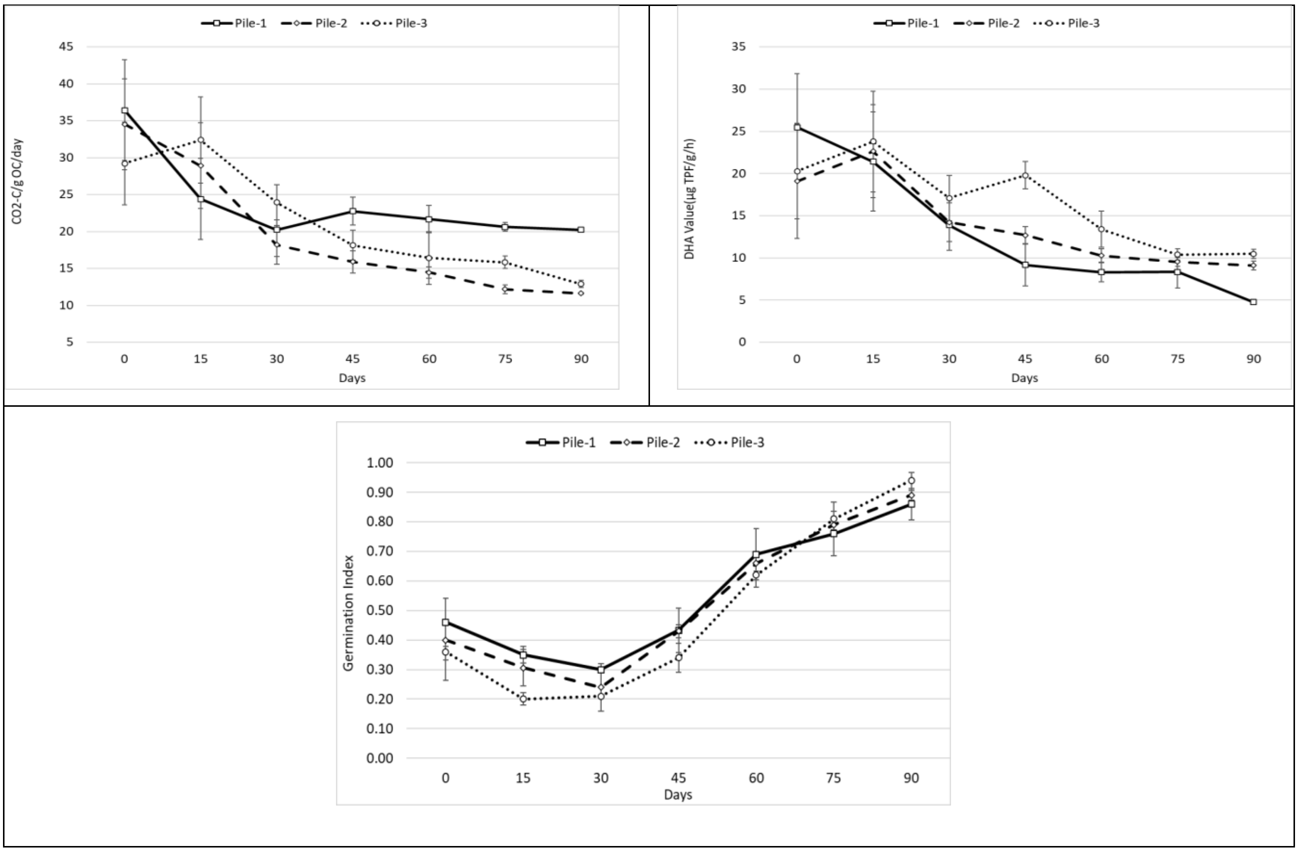

Figure (5). Dynamic changes in dehydrogenase activity (DHA), CO_2 evolution, and germination index (GI) during the composting process of olive mill by-products over 90 days.

B- Olive tree orchard experimentation

Vegetative growth parameters

Existing data in Table 8 demonstrated significant improvements in the shoot length parameter of the Dolce olive cultivar under varying compost treatments, particularly with the use of olive mill pomace (OMP) composts compared to the control. Across the 2022 and 2023 seasons, the application of OMP compost amended with fungal consortium (T3) consistently outperformed other treatments in terms of shoot length with a value of (25.53-25.80 cm) in both seasons, respectively. These findings align with previous studies highlighting the role of organic amendments, especially those inoculated with beneficial fungi, in enhancing nutrient availability and promoting vegetative growth **(Liu *et al.*, 2023**). Although differences in leaf area across treatments were not statistically significant, all compost treatments surpassed the control, demonstrating the beneficial effects of OMP composts.

Table (8). Vegetative growth parameters of Dolce olive cultivar during 2022 and 2023 seasons

Treatments*	Leaf area (cm^2)		Shoot length (cm)	
	2022	2023	2022	2023
T (control)	7.00 a**	7.13 a	23.17 b	21.22 c
T1	7.24 a	7.26 a	23.83 ab	23.22 bc
T2	7.36 a	7.41 a	25.18 ab	24.33 ab
T3	7.48a	7.53 a	25.53 a	25.80 a

* T = usual farm compost. (control); T1 = (OMP + OL + FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL + FM + FC) compost.

** Means having the same letter(s) within the same column are not significantly differ at the probability of 5 % level.

Leaf nutritional status

Data of Table 9 significantly appear to show a narrow variation of the investigated treatments on leaf N, P, and K contents, but each of T1, T2, and T3 was superior to the control. The promotion was recorded in the leaves of trees treated with T3 showed the highest percentage of leaf N, P, and K contents (1.94–2.04%), (0.305–0.255%), and (1.97–1.90%) in both seasons, respectively. in both studied seasons. The minimum values of leaf N, P, and K contents were recorded by the control T in both seasons. This superior performance is attributable to the synergistic effects of fungal inoculants, which have been shown to improve nutrient solubilization and uptake (**Vassileva *et al.*, 2022**). Notably, the application of vermiwash T2 also yielded comparable results, albeit slightly lower than fungal consortium T3, suggesting its potential as an alternative organic amendment **(Makkar *et al.*, 2017).**

Table (9). Leaf minerals contents (g /100g dw) of Dolce olive cultivar during 2022 and 2023 seasons

Treatments*	N (%)		P (%)		K (%)	
	2022	2023	2022	2023	2022	2023
T (control)	1.44 c**	1.54 c	0.213 c	0.216 c	1.56 b	1.61 b
T1	1.63 bc	1.72 bc	0.242 b	0.225 c	1.71 ab	1.68 ab
T2	1.72 ab	1.82 b	0.264 b	0.237 b	1.79 ab	1.78 ab
T3	1.94 a	2.04a	0.305 a	0.255 a	1.97 a	1.90 a

* T = usual farm compost. (control); T1 = (OMP + OL + FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL + FM + FC) compost.

** Means having the same letter(s) within the same column are not significantly differ at the probability of 5 % level.

Flowering parameters

The flowering characteristics of the Dolce cultivar that are presented in Table10 show a statical difference in each of the inflorescence length, flowering density, and sex ratio. The highest values of inflorescence length (3.00-3.11 cm), flowering density (18.33-23.11) and sex expression ratio (71.53-75.60%) showed by the application of T3 that tends to have pronounced significant increase during 2022 and 2023 seasons respectively. Otherwise, the control treatment gave the lowest values. Moreover, the application of T2 followed T3 application and superiority than T1 in both seasons. These findings support the hypothesis that organic composts enriched with microbial inoculants enhance reproductive traits by promoting hormonal balance and nutrient availability **(Mohammed and Muslat, 2023**).

Table (10). Flowering characteristics of Dolce olive cultivar during 2022 and 2023 seasons

Treatments*	Inflorescence length (cm)		Flowering density		Sex ratio (%)	
	2022	2023	2022	2023	2022	2023
T (control)	2.77 b	2.83 b	12.67 d	14.89 d	46.08 d	52.01 d
T1	2.82 ab	2.98 ab	14.67 c	18.22 c	63.63 c	64.54 c
T2	2.96 ab	3.02 ab	16.00 b	20.30 b	68.17 b	66.17 b
T3	3.00 a	3.11 a	18.33 a	23.11 a	71.53 a	75.60 a

* T = usual farm compost. (control); T1 = (OMP + OL + FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL + FM + FC) compost.

** Means having the same letter(s) within the same column are not significantly differ at the probability of 5 % level.

Fruit set, yield/tree and fruit oil content

Results presented in Table 11 declared that, all treatments significantly increased fruit set and yield/tree compared with control. In this concern, the maximum percentage of fruit set (32.89–35.08) and yield/tree (22.33–23.83 kg/tree) is associated with fungal consortium in T3 application. However, the minimum value was obtained by the control treatment. Concerning fruit oil content (%) in dry weight, data in Table 11 indicated that, fruit oil content of Dolce cv. was significantly affected by all treatments as compared to control. The application of T3 gave the highest fruit oil content (28.17% and 28.46%). Additionally, each of the T2 and T1 treatments followed the T3 treatment, but there appear to be no significant differences between them in both seasons. while the control treatment (T) acquired the least fruit oil content (23.89% and 24.51%) in both seasons, respectively. Therefore, it is clear that using the OMP composts, especially fungal consortium T3, has positive effects on olive production. These outcomes emphasize the importance of integrating fungal inoculants in organic composting to achieve optimal yield and quality **(Ahmed *et al.*, 2023**).

Table (11). Fruit set, yield and oil content of Dolce olive cultivar during 2022 and 2023 seasons

Treatments*	Fruits set (%)		Yield/tree (Kg)		Fruit oil (D.W.) %	
	2022	2023	2022	2023	2022	2023
T (control)	25.72 d**	27.67 d	13.50 c	15.33 d	23.89 b	24.51 b
T1	28.22 c	31.22 c	18.43 b	19.67 c	25.05 ab	25.33 ab
T2	30.99 b	33.67 b	20.50 b	21.33 b	26.13 ab	26.05 ab
T3	32.89 a	35.08 a	22.33 a	23.83 a	28.17 a	28.46 a

* T = usual farm compost. (control); T1 = (OMP + OL + FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL + FM + FC) compost.

** Means having the same letter(s) within the same column are not significantly differ at the probability of 5 % level.

Fruit characteristics

It is seen from the present data existing in **Error! Not a valid bookmark self-reference.** that, the application of OMP composts considerably enhanced the fruit quality in terms of increasing the length, diameter, weight of fruit and flesh/fruit (%) compared with control treatment. Applying T3 recorded maximum values of most studied parameters. The obtained fruit length, diameter, and weight were (3.42-3.14 cm), (1.67-1.60 cm) and (4.71-3.86 g) in both seasons, respectively. However, the minimum values were obtained by the control treatment. Concerning the flesh/fruit weight percentage, both T3 and T2 had significant stimulant effects in the 2022 season, while in the 2023 season, there were no statistical differences among the tested treatments. As regards to the pit characteristics in Table 13, data observed a narrow variation among tested treatments. Moreover, all OMP composts were surpassed by the control. The application of T3 gave the highest significant values in terms of pit diameter (0.79-0.77 cm) and pit weight (0.80-0.81 g) in the 1st and 2nd seasons, respectively, followed by T2 or T1, with no significant differences in between. However, the pit length parameter statistically indicated narrow differences of all OMP composts and surpassed the control treatment in both studied seasons of the trial. In general, we can note that all OMP composts induced these fruit quality parameters more than the control. These findings corroborate earlier research on the role of organic amendments in improving physical attributes of fruits through enhanced soil fertility and microbial activity **(Innangi *et al.*, 2017; Makkar *et al.*, 2017; Vassileva *et al.*, 2022 and Mohammed & Muslat, 2023).**

Table (12). Fruit dimensions (cm), weight (g) and flesh/fruit (%) of Dolce olive cultivar during 2022 and 2023 seasons

Treatments*	Fruit length (cm)		Fruit diameter (cm)		Fruit weight (g)		Flesh /fruit (%)	
	2022	2023	2022	2023	2022	2023	2022	2023
T (control)	3.07 c**	3.01 b	1.50 c	1.49 b	3.37 d	3.47 c	78.93 b	79.54 a
T1	3.15 bc	3.05 ab	1.53 bc	1.49 b	3.69 c	3.59 bc	79.67 b	79.38 a
T2	3.29 ab	3.08 ab	1.58 b	1.50 b	4.46 b	3.70 ab	82.96 a	79.46 a
T3	3.42 a	3.14 a	1.67 a	1.60 a	4.71 a	3.86 a	83.01 a	79.02 a

* T = usual farm compost. (control); T1 = (OMP + OL + FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL + FM + FC) compost.

** Means having the same letter(s) within the same column are not significantly differ at the probability of 5 % level.

Table (13). Pit dimensions (cm) and weight (g) of Dolce olive cultivar during 2022 and 2023 seasons

Treatments*	Pit length (cm)		Pit diameter (cm)		Pit weight (g)	
	2022	2023	2022	2023	2022	2023
T (control)	2.34 b**	2.30 b	0.73 b	0.72 b	0.71 b	0.71 b
T1	2.48 a	2.43 ab	0.75 ab	0.73 ab	0.75 ab	0.74 ab
T2	2.49 a	2.48 a	0.76 ab	0.73 ab	0.76 ab	0.76 ab
T3	2.50 a	2.51 a	0.79 a	0.77 a	0.80 a	0.81 a

* T = usual farm compost. (control); T1 = (OMP + OL + FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL + FM + FC) compost.

** Means having the same letter(s) within the same column are not significantly differ at the probability of 5 % level.

Influence of applied composts on cultivated soil characteristics of olive orchard

Data in Table **14** represented that the application of various compost treatments significantly influenced soil properties, enhancing fertility and biological activity. Notably, the fungal consortium compost (T3) led to the most substantial improvements. Compared to the results previously presented in Table 5, soil organic matter increment % increased from 38.1% in the control to 14.82% with T3, reflecting the high organic content. Available nitrogen levels rose from 1.28 mg/kg to 1.43 mg/kg, and available phosphorus increased from 3.5 mg/kg to 3.72 mg/kg, indicating enhanced nutrient availability. These findings align with previous studies demonstrating that compost amendments elevate soil organic matter and nutrient content, thereby improving soil fertility **(Kebede *et al.*, 2023)**. Additionally, dehydrogenase activity, a marker of microbial activity, increased from 7.91 to 25.00 µg TPF/g/h with T3, suggesting stimulation of soil microbial communities. This enhancement in biological activity is consistent with research highlighting the role of compost in boosting soil microbial functions **(Aguilar-Paredes *et al.*, 2023).** Overall, the incorporation of compost, particularly those enriched with fungal consortia, effectively improves soil chemical and biological properties, promoting sustainable soil health and productivity.

Economic evaluation

Data in Table 15 highlights improvements as a result of different compost applications on the olive Dolce cultivar, in terms of yield/fed compared to the control T (2.42 ton/fed), with T3 (3.88 ton/fed) consistently yielding the highest profits. The T3 application achieved the greatest net profit (EGP 48,484), attributed to its enhanced nutrient content and efficiency in boosting fruit yield. While T1 and T2 treatments also delivered substantial financial benefits. On contrary, the control treatment gave the less net return (EGP 21,300). T3's fungal consortium demonstrates the most effective combination of cost efficiency and yield improvement. This emphasizes the economic viability of adopting enriched composts, particularly fungal consortium T3, for sustainable and profitable olive farming in Egypt.

Table (14). Average of Influence of applied composts on cultivated soil characteristics of olive orchard

Soil properties	Treatments			
	T (control)	T1	T2	T3
pH (compost water suspension 1:5)	7.86	7.50	7.40	7.30
EC Value (dS/m at 25ºC) (compost water extract 1:10)	5.15	5.80	5.60	6.00
Available N (mg kg^{-1})	1.30	1.22	1.31	1.43
Available P (mg kg^{-1})	3.43	3.61	3.54	3.72
Available K (mg kg^{-1})	75.12	73.08	75.36	75.42
Organic matter (%)	0.29	0.28	0.27	0.24
CO_2-C/g OC/day	18.72	20.50	22.00	25.00
DHA (µg TPF/g/h)	7.91	20.50	22.00	25.00

T= usual farm compost. (control); T1 = (OMP + OL+ FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL+ FM + FC) compost.

Table (15). Economic evaluation of applied composts of the Dolce olive cultivar

Treatments	Average yield/fed (ton)	Total income /treatment/fed (EGP)	Total cost/fed/ year (EGP)		Total cost /fed/year (EGP)	Net profit
			Fixed cost	Compost cost		
T (control)	2.42	48,400	25,000	2,100	27,100	21,300
T1	3.20	64,000	25,000	3,780	28,780	35,220
T2	3.51	70,200	25,000	3.864	28,864	41,336
T3	3.88	77,600	25,000	4,116	29,116	48,484

T= usual farm compost. (control); T1 = (OMP + OL+ FM) compost; T2 = (OMP + OL + FM + VW) compost; & T3 = (OMP + OL+ FM + FC) compost.

4. Conclusion

This study highlights the successful integration of olive mill pomace composts, enriched with biological agents such as fungal consortia, vermiwash, and farmyard manure, into olive orchard management. The composts demonstrated substantial improvements in soil fertility, microbial activity, and nutrient availability. Field trials observed that fertilization with three olive waste composts, especially (T3), enhanced vegetative growth, flowering density, fruit yield, and oil content, with the fungal consortium treatment consistently outperforming other amendments. These findings support the potential of bio-amended composts in sustainable olive cultivation, offering a resource-efficient solution to agricultural waste management. The results underscore the importance of innovative composting strategies in promoting circular economy practices, improving soil health, and achieving long-term productivity in olive farming systems. Furthermore, producers and the ecological agricultural system can readily implement this safe way of recycling olive waste into compost.

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تحسين الأنتاجية المستدامة لأشجار الزيتون بإستخدام المخصبات الحيوية لإنتاج كمبوست من مخلفات عصر الزيتون

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يتناول هذا البحث مدى تكامل واستدامة إدارة مخلفات الزيتون وزراعته مع الأقتصاد الدائري من خلال تحسين الإنتاجية وتخفيف الأعباء البيئية. و تستعرض الدراسة عملية تحويل تفلة الزيتون إلى كمبوست باستخدام مخصبات بيولوجية مثل مستخلص سماد الدودة والتلقيح بالفطريات المحللة لليجنوسيليولوز(*Phanerochaete chrysosporium* و *Trichoderma* sp.) والسماد البلدى، كما تم تقييمها كسماد عضوي لتحسين خصوبة التربة، وتحسين نمو شجرة الزيتون، وزيادة الإنتاجية. تم عمل كمرللكمبوست في شهر يونيه 2021 حيث تم تقسيمه الى ثلاث أكوام كالاتى : الكومة1 (تفلة الزيتون + أوراق الزيتون + سماد بلدي)، الكومة 2 (تفلة الزيتون + أوراق الزيتون + سماد بلدي + مستخلص سماد الدودة)، والكومة 3 (تفلة الزيتون + أوراق الزيتون + سماد بلدي + التلقيح بالفطريات)، كما تم اضافة اليوريا بنسبة (0.25%) وصخر الفوسفات بنسبة (3%) لكل كومة. اشتملت الدراسة متابعة عملية كمر الكمبوست من خلال متابعة التغيرات الديناميكية فى درجات الحرارة، ومستوى الحموضة، والتوصيل الكهربائي، وتحلل المادة العضوية، لإبراز كفاءة المخصبات البيولوجية في تحقيق الظروف الحرارية، وثبات العناصر الغذائية، ونضج كومات الكمبوست.تم اضافة كومات الكمبوست الثلاثة التى تم تجهيزها في ديسمبر إلى أشجار الزيتون صنف الدولسي التي تبلغ من العمر 15 عامًا ومقارنتها بالاشجار التى تم تسميدها بسماد المزرعة خلال موسمي الزراعة (2022 و2023) وذلك لتقييم تأثيرها على النمو الخضري لأشجار الزيتون، الحالة الغذائية للأوراق، الإزهار، تكوين الثمار، خصائص الثمار، المحصول، محتوى الزيت، وخصوبة التربة. أظهرت النتائج تفوق الكمبوست الملقح بالفطريات (تفلة الزيتون + أوراق الزيتون + سماد بلدي + التلقيح بالفطريات) في تحسين خصوبة التربة، وتوافر العناصر الغذائية، ومحصول الزيتون، صافي الربح، مما يدعم استخدامه في الزراعة المستدامة. تشير نتائج التجربة، إلى أن استخدام مخلفات الزيتون المحولة لا غنى عنها لتحسين الحالة الغذائية للأشجار وخصوبة التربة، مما يزيد من المجصول وجودة الثمار وبالتالي الإنتاجية والدخل الصافي، وتقليل كمية الأسمدة والتلوث البيئي الناجم عن هذه النفايات.

الكلمات الدالة: تفلة الزيتون؛ الكمبوست المخصب حيويا؛ الفطريات المحللة لللجنوسيليلوز ؛ مستخلص سماد الدودة؛ إنتاجية الزيتون.