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Review Article

Olive Mill Pomace Compost as Soil Amendment, and Sources of Biopesticides and Animal Feed: A Review

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Abstract

The world's main challenge is to increase crop productivity in a sustainable manner. Every agricultural management decision should prioritize human health and environmental safety. Olive mill pomace (OMP) must be disposed of practically and affordably because it exacerbates environmental issues. If OMP is properly handled, it has the potential to be used in agriculture for sustainable production. Many approaches have been widely investigated in recent years as a result of environmental protection policy to improve the recycling of OMP through composting or use as fertilizers, biopesticides, and livestock feed. However, there was no comprehensive work that covered the role of OMP in improving soil properties, as well as sources of biopesticides and animal feed. The potential use of OMP as a fertilizer, biopesticide, and animal feed was discussed in this review. As a result, it was found that OMP can be utilized as a high-quality soil fertilizer. It may also be a viable alternative to synthetic pesticides for pest control, as it demonstrated a higher growth rate of beneficial insects. Furthermore, when using OMP as feed for animals showed a potential for tasty meats and healthy milk for ruminants and poultry without affecting their performance and viability. The most significant result of this review paper is that it contributes to the body of knowledge regarding the use of OMP as a sustainable and environmentally friendly product in the production of natural fertilizers, biopesticides, and animal feed.

Keywords: Waste management; Disposal; Fertilizer; Soil infiltration; Biopesticides; Plant protection; Animal feed

Introduction

The world's main challenge is to increase crop production in a sustainable manner. Invasive pest pressures, pesticide misuse, global warming, water scarcity, land degradation, and biodiversity loss all have serious consequences for world’s food security (Al-Zyoud 2014c; Deshmukh *et al.* 2021). The above-mentioned factors have already reduced the global food supply and caused a sharp decline in global production, making it difficult to meet the food needs of billions of people. To share improved production practices and technologies with farmers, new technologies must be developed along with education and extension services. In regions with low yields, new production systems must be developed and adapted for long-term productivity under specific ecological conditions (Al-Zyoud 2014a, b).

Olive cultivation for oil production is one of humanity's oldest agricultural practices (Sciubba *et al.* 2020). Olive oil is a key component of the Mediterranean diet because of its high nutritional value and health benefits. Olive oil consumption has gradually increased globally in recent decades due to increased awareness of its health benefits, gastronomic properties, and population growth (Ortega 2006), and thus olive growing area is expanding on an annual basis (Mili 2006). Olive oil has superior nutritional, sensorial, and functional properties (Baccouri *et al.* 2008). Furthermore, due to its high oleic acid content and the presence of antioxidants, olive oil has many beneficial effects, such as preventing certain diseases and improving overall human health (Shdiefat *et al.* 2009). There are over 800 million olive trees in the world, covering a total area of 10 million hectares (Abu-Rumman 2016). Olives are used either as pickled olives or to produce olive oil. The global production of table olives is estimated at 2.9 million tons, while olive oil production exceeds 3.3 million tons. It is worth noting that the Mediterranean region produces 97% of the world's olive oil (IOOC 2021).

Three processes are used to extract oil: the traditional process (press process), the two-phase process, and the three-phase process (Azbar *et al.* 2004). The extraction of olive oil generates a large amount of byproducts, including olive mill wastewater (OMW) and olive mill pomace (OMP). These two byproducts pollute the environment significantly due to their unpleasant odor and color, acidic

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pH, high organic load, salinity, and phenolic compounds (Mekersi *et al.* 2021). The most common extraction process produces three phases: an oily phase (oil, 20%), a solid residue (OMP, 30%), and an aqueous phase (OMW, 50%) (Jerman and Vodopivec 2012; Omer and Mohamed 2012). Between November and February, the Mediterranean countries produce a large amount of OMP (Mechri *et al.* 2008). One of the benefits of the 2-phase mill production system is that it uses less water and reduces waste production by 75% (Roig *et al.* 2006). Depending on the extraction system used, an estimated average volume of OMW of 0.3–1.2 m^3/ton and quantity of OMP of 500–735 kg/ton of processed olive have been reported (Barbera *et al.* 2013; Khdair and Abu-Rumman 2020).

The OMP is a solid by-product of olive oil production that contains water, stone skin, olive pulp, and pit fragments, with a dry weight concentration of up to 94% (Abu-Rumman 2016; Al-Ananzeh *et al.* 2016). Because the OMP is phytotoxic and contains phenolic compounds, lipids, and organic acids, it exacerbates environmental problems; therefore, it must be disposed of practically and feasibly. If OMP is properly treated, it can be used in agriculture as an ecofriendly, high-quality compost because it contains a high organic matter content and a wide range of plant nutrients that can be reused as fertilizers for sustainable agricultural production (Chowdhury *et al.* 2013). Selim *et al.* (2020) used bioactive compounds derived from OMP to improve the quality of toast bread, and their findings are summarized in Table 1.

Spreading solid waste on farmlands pollutes both the soil and the air, and the waste leaves cluttered environmental footprints (Omer and Mohamed 2012; Dermeche *et al.* 2013; Galanakis 2017). Because of the deterioration of freshwater and scarcity of agricultural water resources (Mamkagh 2009; Mamkagh and Anderson 2018; Al-Dabbas *et al.* 2021), proper disposal of OMP is critical to reduce its negative effects on groundwater (Tawarah and Rababah 2013). Other reported potential uses of OMP include fertilizers (Haddadin *et al.* 2009), an effective alternative to synthetic pesticides (Cayuela *et al.* 2008), animal fodders (Haddadin and Abdulrahim 1999), and a source for the manufacture of activated carbon (Mameri *et al.* 2000). Many approaches have been widely investigated to improve the recycling of OMP through composting (Parascanu *et al.* 2018), or to use it as construction materials, livestock feed, biofuel, and thermal insulation (Chouchene *et al.* 2010), pharmaceutical, food, chemicals (biopesticides), and energy (Asveld *et al.* 2011) (Fig. 1).

This strategy's OMP is used in three sectors: food and feed, industrial products, and bioenergy. Thus, the higher value in the Pyramid represents food and feed, which would be used first before reaching utilization for energy generation. Surprisingly, the majority of countries, including those in the Middle East, use and apply OMP for bioenergy and biofuels, which are at the bottom of the value pyramid.

Due to the fact that raw OMP includes significant quantities of phytotoxic chemicals that might harm both the soils and the plants, it cannot be added to the soils without prior treatment (Pages *et al.* 1982). However, when OMP is used as a soil amendment after composting, it can significantly reduce phytotoxicity, and may benefit soil and plant growth and development (Komilis and Tziouvaras 2009). Similarly, when OMP was used as a livestock feedstuff, it showed promising results in terms of lowering feed costs in countries with limited feed supply and high feed prices (Al-Atiyat 2014), as well as improving meat and dairy product quality (Berbel and Posadillo 2018). Nevertheless, for the aforementioned considerations, we conducted a systematic literature search for relevant works on OMP. However, there has been no comprehensive study of the role and value of OMP biomass in improving soil properties, and as sources of biopesticides and animal feed. Thus, in this review we focused on soil properties, fertilizers, infiltration, OMP as biopesticides and their role in plant protection, human and environmental safety, soil-borne plant pathogens, and their value in animal feed. The most important result of this review paper is that it adds to the global pool of knowledge about OMP and fills a gap in the literature about the use of OMP as an environmentally friendly pest control tactic, a source of animal feed, and potential effects on soil when used as natural fertilizers.

Methodology

Herein, we conducted a systematic search of literature for relevant works on OMP. The OMP data were obtained from the websites of Web of Science, Google Scholar, Scopus (Elsevier), and ResearchGate. The following keywords were used in our search: olive, *Olea europaea*, olive by-products, olive mill pomace, olive-mill solid waste compost, solid residue phase, organic composts, compost amendments, soil properties, fertilizer compost, infiltration, water holding capacity, and nutrients. Furthermore, the following keywords were used in the field of plant protection: integrated pest management (IPM), sustainability, biopesticides, plant protection, human and environmental safety, alternative pest control methods, ecofriendly sound pest control tactic, cost-effective control, soil-borne plant pathogens, air-borne plant pests, plant diseases, nematodes, and soil microorganisms. Furthermore, the following terms were used in the field of animal production: animal feed, livestock husbandry, poultry, meat and milk quality, small ruminants, metabolic energy, and animal performance.

Compost preparation and soil physical properties

Compost preparation: To make the compost, OMP was mixed in a 1:2 ratio with olive leaves. The mixture was then placed in a covered rectangular windrow for 60 days, and turned weekly. Tap water was added as needed to keep the moisture level around 50%. Following that, the compost was removed from the windrow to mature before being piled in a covered area for other 60 days. Several samples, each weighing 10 g, were taken from the compost during the trail to assess phytotoxicity using the germination index. Finally, the compost made from OMP and leaves contains enough nutrients to be a high-quality soil amendment, and it is better suited for small olive mill plants due to the short composting period (Michailides *et al.* 2011).

Compost and soil chemical and physical properties

Several studies found that using OMP compost improved soil chemical and physical properties because an increase in nutrients, particularly nitrogen, potassium, and phosphorous, is required by plants (Sellami *et al.* 2008; Buono *et al.* 2011). Composting is a natural bio-chemical aerobic process of organic waste materials, such as agricultural wastes, that can enrich the soil and plants by providing an ideal environment for decomposing organisms. Composting consists of three stages: initial activation, thermophilic, and mesophilic decomposition (Ryckeboer *et al.* 2003). Microorganisms produce water, minerals, carbon dioxide, and stabilized organic matter (Giusquiani *et al.* 1995), so that caution is required because the absence of environmental control during the process will result in natural degradation and rotten.

Nonetheless, the most important components of compost, such as phosphorous, nitrogen, organic matter, and trace elements, have a positive effect on soil fertility and structure, thus increasing agricultural productivity (Senesi 1989). Compost, as an alternative fertilizer, improves soil infiltration and water holding capacity by increasing microbial activity compounds, improving aggregate stability and cation exchange, and increasing aggregate stability (Cooperband 2002). OMP must be composted for at least 18 weeks to eliminate any phytotoxic effect and make it easier to manage (Cayuela *et al.* 2007). Composting can sanitize and stabilize OMP, as well as reduce its mass and volume before mixing it with soil. Composted OMP has the same amount of organic matter as horse, pig, and rabbit manures and more than cow, sheep, and poultry manures. It is preferable to compost OMP with natural organic residues such as manures, straws, olive twigs, and leaves, allowing them to decompose in aerated piles for 7–9 months (Gomez-Munoz *et al.* 2012).

OMP addition effect on soil properties

Bueno *et al.* (2014) investigated the effect of compost made from OMP on the physical and chemical properties of sandy loam soil with low organic matter levels and no salinity issues. The compost was made by combining OMP with olive leaves and horse manure. The following are some of the main chemical properties of the tested compost: 9.46 pH, 67.00 organic matter, 1030 mS/cm electrical conductivity, 1.85 g/kg nitrogen, 0.36 g/kg phosphorus, and 2.00 g/kg potassium. The addition of OMP compost significantly reduced hydraulic conductivity, while increasing organic matter in the soil. Furthermore, it was reported that the electrical conductivity of the soil increased immediately after the application of compost, but rapidly decreased with the passage of time. The authors attributed this discovery to the ease with which the high initial salt contents were washed away by consecutive irrigation. Moreover, Abu-Rumman (2016) investigated the effect of varying proportions of fresh OMP on the bulk density, accumulated intake, and water holding capacity of clay and sandy clay soils. Table 2 displays the physicochemical properties of the tested OMP samples. When, OMP was added to the soil at the start of the experiment, there were no changes in soil infiltration. This finding was attributed to a decrease in water advance and penetration caused by an increase in soil water holding capacity. The same study demonstrated that soil with OMP compost takes less time to reach its maximum water holding capacity. During the experiment, there was also an increase in cumulative water intake in the sandy soil initially, followed by the clay soil. As a result of the positive effects on soil physical properties, it is recommended to use OMP as a soil amendment. It should be noted that untreated OMP from a three-phase olive mill was used as a soil amendment without considering the potential negative effects on the soil and the environment (Abu-Rumman 2016).

In 2019, Diacono and Montemurro studied the effects of OMP compost on soil characteristics and heavy metals in both plants and soil. Fresh OMP was obtained from a two-phase olive oil mill. Eighty-two kg of OMP were combined with 10 kg of poultry manure and 8 kg of wheat straw to make the compost. Following that, the mixture was continuously stirred in an open field to ensure oxidation and homogeneity. The temperature of the mixture ranged between 50°C and 60°C during the thermophilic phase of composting (40 days), and between 35°C and 45°C during the mesophilic phase (150 days), while the moisture ranged between 50 and 60% almost throughout the preparation time. Table 2 shows the main chemical properties of the compost obtained during the experiment. However, no significant accumulation of heavy metals in the soil was observed, so the authors proposed recycling olive mill wastes in an environmentally friendly manner by using the OMP compost to produce a useful nitrogen source in organic farming and to reduce the input of mineral fertilizers in conventional agriculture productions (Diacono and Montemurro 2019).

The role of olive mill pomace in plant protection

Pesticides: Pesticides have aided humans in meeting rising food demand by increasing agricultural output through pest control. Chemical control has been the most commonly used control tactic in recent decades, ensuring high yields for farmers (Al-Zyoud 2014c). After more than 70 years of pesticides' usage worldwide, their side effects on aquatic and terrestrial ecosystems are obvious (Oguh *et al.* 2019a; Siddique *et al.* 2020). Intensive use of pesticides has resulted in increased pest resistance (Muraro *et al.* 2021), and negative environmental and human health impacts (Ghabeish *et al.* 2021). Exposure to pesticides is increasingly linked to human health implications, *i.e*., immune suppression, reproductive abnormalities, nervous system disorders (Campagna *et al.* 2009), cancer (Amanullah and Hari 2011), asthma and diabetes (Jayashree and Singhi 2011), Alzheimer's dementia, Parkinson's diseases, allergies (Hong *et al.* 2014), and death (Raipulis *et al.* 2009). It is reported that pesticides contaminate rivers, groundwater (Pattnaik *et al.* 2020), soil and air (Oguh *et al.* 2019a). According to an estimate, water bodies within 40% of the global land surface are at risk of pesticide pollution (Ippolito *et al.* 2015). High doses and frequent pesticide applications have adversely affected natural enemies (Al-Zyoud 2014c, 2015), birds (Mitra *et al.* 2011), fish and wildlife (Pattnaik *et al.* 2020), beneficial soil microorganisms, plant yields (Glover-Amengor and Tetteh 2008), and caused crop phytotoxicity (Burger *et al.* 2008). Pesticide misuse can also cause undesirable residue accumulation in food crops (Andrade *et al.* 2015). Pesticide residues absorb by plants, enter the food chain and accumulate in human and animal body fats (Pattnaik *et al.* 2020), and may cause serious problems in dairy animals (Choudhary *et al.* 2018). The persistence nature of some pesticides led to their accumulation in animal tissues, organs, muscles and blood, and subsequently causes human dietary exposure to these pesticides through consumption of animal products (Pattnaik *et al.* 2020). Normally pesticides enter into the animal body through contaminated feed, water and through passive diffusion when used as ectoparasiticides (Singh *et al.* 2014). Presence of pesticide residues in tissues and organs of goats, cattle, sheep, lambs and chicken have been reported worldwide (Singh *et al.* 2014). An estimate shows death and chronic diseases due to pesticide poisoning about 1 million cases/year worldwide (Pattnaik *et al.* 2020). However, due to pesticide residues and resistance issues, it has recently become clear that more ecofriendly sound control tactics are urgently needed for agricultural policymakers (Al-Zyoud *et al.* 2021; Lin *et al.* 2021).

Pest management

Pest management is a mean of reducing pest population to an acceptable or economical threshold (Oguh *et al.* 2019b). Studies indicate increased pest resistance to pesticides (Naharki *et al.* 2020), and pesticides becomes ineffective (Mariyono 2008), as well as the complete dependency on pesticides caused adverse effects to environment, human and livestock (Samiee *et al.* 2009). Thus, every pest management decision should prioritize human health and environmental safety (Al-Zyoud 2014a, b). However, sustainable agriculture is a key element of sustainable development and essential to the future of human being (Shojaei *et al.* 2013). Sustainability aims to achieve adequate safe and healthy food production, and improve livelihoods of food producers (Uwagboe *et al.* 2012). Integrated pest management (IPM) is used to manage pest damage by the most economical means and the least hazards to human and environment (Ofuoku *et al.* 2009). IPM is a decision-based process involving coordinated use of multiple tactics for optimizing pest control in an ecologically and economically sound manner (Al-Zyoud 2014a, b). IPM tactics are designed to provide economic benefits, reduce environment and human health risks, and solve the problem of pest resistance to pesticides (Al-Zyoud *et al.* 2015; Naharki *et al.* 2020). The world supports the use of IPM in agriculture as the best environmentally sound approach to pest control (Al-Zyoud *et al.* 2021). To mitigate the ecotoxicological, environmental, and social consequences of synthetic pesticides, it is therefore critical to investigate effective, economical, safe, and ecological alternative pest control methods compatible with sustainable development (Carvalho 2017).

Use of OMP as biopesticides in crop pest management

Olive pomace as a source of biopesticides: During the past three decades, efforts have been made to reduce the exposure and human risk of pesticides, thus, some conventional pesticides have been replaced by newer bioiopesticides. Biopesticides are third-generation pesticides that are environmentally friendly and closely resemble or are identical to chemicals produced in nature (Niassy *et al.* 2021; Paredes-Sanchez *et al.* 2021). Biopesticides are effective, biodegradable with no residuals in the environment (Tijjani *et al.* 2016). Biopesticides are naturally occurring substances from living organisms (natural enemies) or their products (microbial products, phytochemicals) or their by-products (semiochemicals) that can control pests by nontoxic mechanisms (Salma and Jogen 2011; Bateman *et al.* 2021; Lin *et al.* 2021; Niassy *et al.* 2021; Paredes-Sanchez *et al.* 2021). Biopesticides fall into four major categories: microbial pesticides (Chandler *et al.* 2011), biochemical pesticides (Pal and Kumar 2013), plant-incorporated-protectants (Deshmukh *et al.* 2021), and semiochemicals (Al-Dosary *et al.* 2016). Biopesticides are pesticides made by organisms usually for their own defense, or are derived from a natural source such as plant, animal, bacteria, and certain minerals, use to control pest naturally with less effect or no effect (Oguh *et al.* 2019a, b). Biopesticides usually target specific sites in the insect such as nervous system, resulting in knock-down, lack of coordination, paralysis and death (Oguh *et al.* 2019b). Most botanical pesticides show their effect through contact, respiratory, or stomach poisons to the target organism. Botanical pesticides are generally highly bio-degradable, and they become inactive within hours or a few days and can easily be

Table 1: Composition of fresh OMP (g/100 g) (Two-phase olive oil extraction)

Physicochemical properties	Value
Moisture	64.58 ± 2.51
Total lipids	02.33 ± 0.06
Protein	02.48 ± 0.04
Ash	01.13 ± 0.02
Carbohydrates	29.48 ± 2.41
Cud fiber*	20.37 ± 1.65
Cellulose*	40.77 ± 2.44
Hemicelluloses*	33.63 ± 2.28
Lignin*	19.50 ± 1.79

*Calculated as a percentage from OMP fiber (% on a dry weight basis) (Adopted from Selim *et al.* 2020)

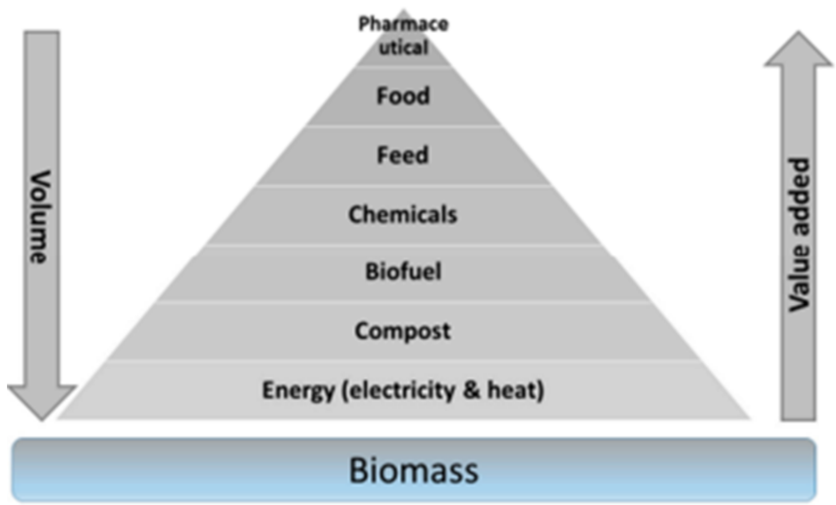

Fig. 1: Pyramid of biomass value (Adopted from Asveld *et al.* 2011)

broken down by stomach acids in mammals, so toxicity to humans and animals is very low (Oguh *et al.* 2019b). The recognized categories of bio-pesticides may be synthetic or natural compounds of microbial, plant protectant and biochemical (pheromones, hormones, natural growth regulators and enzymes) origins (Dimetry 2012; Oguh *et al.* 2019b). Biopesticides are considered as eco-friendly safer for user, rapid degradation, narrow spectrum of activity, cheaper, less toxic to workers or consumers; safer for beneficial insects, may be used shortly before harvesting, act very quickly inhibiting insect feeding, not phytotoxic, and resistance to these compounds is not developed as quickly as with synthetic pesticides (Oguh *et al.* 2019b), thus biopesticides should be the first choice for pest management, which in turn reduces the bioavailability of metal and noxious effect in the environment.

Biopesticides are the best candidates for sustainable integrated crop productivity and pest management as an alternative to synthetic pesticides (Drobek *et al.* 2019; Ogunnupebi *et al.* 2020). Many researchers have been inspired to use bioactive molecules with growth promotion and antimicrobial effects found in OMW by-products as biopesticides for crop protection. Biopesticides have recently been identified as the best candidates for phytopathogen control in sustainable agriculture (Sciubba *et al.* 2020). Organic soil amendments have the potential to be safer alternatives to the harmful synthetic pesticides that are currently used to control plant pests (Sasanelli *et al.* 2011). The OMP has antimicrobial activity and anti-pest properties, possibly due to the presence of bioactive molecules such as phenols and polysaccharides and is expected to drive the future development of more sustainable agriculture (Sciubba *et al.* 2020). Compost made from plant debris is viewed as a viable alternative to synthetic chemicals for improving plant growth by improving soil physicochemical properties, nutritive effects, and nutrient content (Scotti *et al.* 2016). Aside from their high agronomic value, several studies have reported their potential use as biopesticides and suppressive abilities against many soil- and air-borne plant pathogens (Corato *et al.* 2019; Coelho *et al.* 2020). As a result, composting is regarded as the most effective and environmentally safe treatment for producing an agronomically beneficial organic amendment. This is an environmentally safe, efficient, and cost-effective treatment for recycling biodegradable materials, typically organic mixtures, resulting in a stabilized end product known as compost (Maniadakis *et al.* 2004). Compost is a renewable organic resource that can be widely used in agriculture to control pests and improve plant health (Liguori *et al.* 2015;

Table 2: Physicochemical and chemical properties of compost made from OMP extracted using a two-phase olive oil mill

Physicochemical properties	Value	Chemical properties	Value
Temperature (°C)	25	pH	8.63
Moisture content (Fresh weight %)	70	Zinc (Zn) (g/kg)	0.202
pH	5.40	Total nitrogen (g/kg)	23.44
Conductivity (dS/m)	4.35	Copper (Cu) (g/kg)	98.81
Total nitrogen (g/kg)	12.4	Phosphorus (P) (g/kg)	7.053
Carbon/Nitrogen (C/N)	32.20	Lead (Pb) (mg/kg)	30.82
Phosphorus (P) (g/kg)	0.90	Nickel (Ni) (mg/kg)	05.55
Sodium (Na) (g/kg)	0.70	Total organic carbon (TOC) (g/kg)	245.2
Potassium (K) (g/kg)	0.90	Dry matter (%)	84.6
Calcium (Ca) (g/kg)	2.30	Crude protein (%)	9.02
Total organic carbon (TOC) (g/kg)	590.0	Crude fat	7.6
Ash (g/kg)	72.40	Crude fiber	40.6

(Adopted from Youssef *et al.* 2001, Abu-Rumman 2016; Diacono and Montemurro 2019)

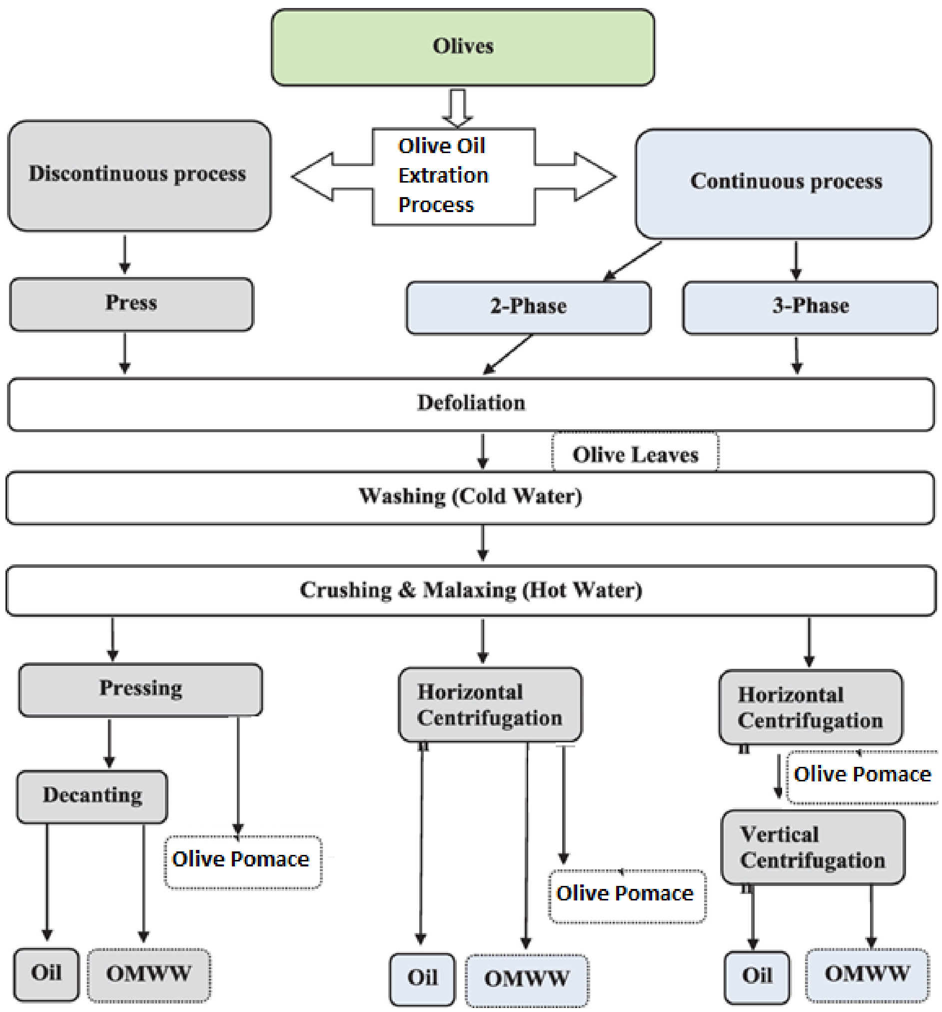

Fig. 2: Scheme of extraction methods. (OMWW = olive mill wastewater)

Corato *et al.* 2018). In fact, compost amendment improves crop yield by suppressing soil-borne pathogens (Mahadevakumar *et al.* 2016). The disease-suppressing potential of composts is governed by their microbial consortium and the ability of their associated beneficial bacteria to compete with the target plant pathogen.

The role of OMP in pest management

Regarding fungal pathogens that caused huge losses to crops, it has been found that composts are capable of suppressing soil-borne plant pathogens more efficiently than synthetic fungicides such as tebuconazole and

Table 3: Effects of olive mill pomace' compost as a biopesticide against different pests and their host plants (crops)

Pest	Crop	Reference
Verticillium wilt disease (*Verticillium dahliae*)	Olive	Varo-Suarez *et al.* (2017)
Onion white rot disease (*Sclerotinia cepivorum*)	Onion	Martin and Ramsubhag (2015)
Lettuce root rot disease (*Sclerotinia sclerotiorum*)	Luttuce	Martin and Ramsubhag (2015)
Phytophthora root rot disease (*Phytophthora nicotianae*)	Tomato	Ntougias *et al.* (2008)
Stem rot disease (*Sclerotium rolfsii*)	Tomato	Ayed *et al.* (2022)
Verticillium wilt disease (*Verticillium dahliae*)	Pepper	Tubeileh and Stephenson (2020)
Root-knot nematode (*Meloidogyne incognita*)	Cantaloupe	D'Addabbo *et al.* (2003)
Fruit rot disease (*Sclerotium rolfsii*)	Pumpkin	Mahadevakumar *et al.* (2016)
Rhizoctonia damping-off disease (*Rhizoctonia solani*)	Bean	Corato *et al.* (2019)
Verticillium wilt disease (*Verticillium dahliae*)	Eggplant	Corato *et al.* (2019)
The mold pathogens: *Aspergillus clavatus*, *Aspergillus flavus*, *Aspergillus terreus*, *Aspergillus niger*	Alfalfa	Omer and Mohamed (2012)
Root-knot nematode (*Meloidogyne incognita*)	Tomato	Kavdir *et al.* (2019)
Root-knot nematode (*Meloidogyne incognita*)	Tomato	Radwan *et al.* (2009)
Common purslane, redroot pigweed and jungle rice weeds	Okra	Boz *et al.* (2009)
Little seed canary grass, annual bluegrass, wild chamomile, and shepherd's-purse weeds	Faba bean and onion	Boz *et al.* (2009)

vinclozolin in controlling the onion white rot induced by *Sclerotinia cepivorum* and the lettuce root rot caused by *S. sclerotiorum* (Martin and Ramsubhag 2015). Studies showed the suppressive capacity of organic composts against various soil-borne diseases induced by *Fusarium oxysporum*, *Rhizoctonia solani*, *Verticillium dahliae*, *S. minor*, *S. sclerotiorum*, *Phytophthora infestans* and *Pythium ultimum* associated with different host plants (Mahadevakumar *et al.* 2016; Corato *et al.* 2019; Tubeileh and Stepgenson 2020). The OMP had inhibitory effects on the plant pathogens; *Aspergillus clavatus*, *Aspergillus flavus*, *Aspergillus terreus*, *F. oxysporum* and *Verticillim dhaliae* (Alfano *et al.* 2011; Omer and Mohamed 2012). The higher inhibition capability of mature compost may be explained by the formation of toxic metabolites by some microbial communities that developed in the piles during the composting process (Cayuela *et al.* 2008). In a plate-inhibition experiment, OMP exerted a significant inhibitory effect on the growth of *F. oxysporum f.* spp. *lycopersici* and *P. ultimum* (Gabriele *et al.* 2011). In potted experiment to assess the effect of OMP against soil- and air borne pathogens of tomato, it was reported that OMP has a high level of suppressiveness against *Phytophthora nicotianae* in tomato (81–100% reduction in plant disease incidence) (Ntougias *et al.* 2008). Taken into account that stem rot caused by *Sclerotium rolfsii* is one of the most devastating diseases in tomato (Sun *et al.* 2020), a mixture includes OMP was evaluated for its ability to control this disease and to promote tomato plant growth. The tested compost was effective in decreasing disease severity from 31.2 to 56.2%, and has significantly enhanced tomato-growth parameters *i.e.*, plant height, stem diameter, and dry weights of aerial parts and roots (Ayed *et al.* 2022). These findings agreed with those of Tubeileh and Stephenson (2020) who found the highest disease control potential of OMP against *P. nicotianae* and *V. dahliae*.

The use of organic amendments could represent one of the possible alternatives to synthetic nematicides in the control of nematodes. An OMP incorporated into a soil infested by the root-knot nematode, *Meloidogyne incognita* was found to suppress *M. incognita* in tomato glasshouse experiments. The number of eggs and juveniles of nematodes on cantaloupe roots and in the soil were significantly reduced in the OMP treatment compared to the untreated control (D'Addabbo *et al.* 2003). In-vitro conditions, the efficacy of OMP at different rates was evaluated against the 2nd stage juveniles (J2) of *M. incognita* mixed with sandy loam soil at different rates under controlled conditions on tomato, and it was found that OMP reduced *M. incognita* by 53% as compared to the control. Higher rates of OMP added into the soil resulted in healthy and much longer root systems, and higher plant fresh and dry weights than those in the control treatment (Kavdir *et al.* 2019). In addition, *M. incognita* populations in the soil and root galling were significantly reduced when OMP was added to the soil, and OMP was the most effective when applied at the highest rate (50 g/kg), since it reduced J2 in the soil by 92%. Thus, OMP could prove to be a main component of IPM for the root-knot nematodes in plants in organic farming (Radwan *et al.* 2009).

Field experiments were carried out to evaluate the weed control efficacy of OMP in okra, faba bean, and onion. The OMP was incorporated into the soil prior to seeding at 10, 20, 30 and 40 t/ha, and it was found that OMP control common purslane, redroot pigweed, and junglerice weed in okra; little seed canary grass, annual bluegrass, wild chamomile, and shepherd's-purse in faba bean and onion. The OMP was in most cases equally as effective as soil synthetic herbicides, and OMP had no negative effects on plants. Overall, OMP can be applied at a rate of 10-20 t/ha for weed control with adequate crop safety (Boz *et al.* 2009). Concerning beneficial insects, a study was evaluated the effect of environmentally realistic concentrations of OMP on the growth, reproduction and survival of the earthworms, *Aporrectodea trapezoides* and *Eisenia fetida*. Results showed a higher growth rate of *E. fetida* when exposed to 12.5% OMP (Mekersi *et al.* 2021). Examples of using OMP compost as a biopesticide against some pests on crops are listed in Table 3.

The role of OMP in animal feed

The OMP is used as an alternative to traditional feed resources in every country where the olive oil industry exists, in addition to the other uses mentioned in the preceding sections. Indeed, livestock husbandry in the dry areas of the Mediterranean Basin faces scarcity and fluctuation in feed supply and feed prices (Al-Atiyat 2014). Thus, OMP has been successfully used as a source of animal feed in the livestock industry in the Mediterranean region. Nonetheless, using OMP for animal feed lowers feeding costs while improves the quality of meat and other dairy products (Berbel and Posadillo 2018). The use of OMP has no negative effects on milk production or the fattening of small ruminants (Tzamaloukas *et al.* 2021). Indeed, these authors found that OMP increases monounsaturated fatty acid levels while decreasing saturated fatty acid levels in both milk and meat, resulting in positive health effects for consumers. It is worth noting that the percentage of protein in OMP containing stones is around 5%, whereas the percentage of protein in bagasse from which the stones were completely removed is around 12%. In both cases, OMP's protein contains low levels of essential amino acids, which is an important factor in determining its nutritional value, particularly when used in rations without the use of chemicals. The percentage of fat in the OMP, on the other hand, varies, and this is primarily determined by the method of extracting oils from the olive during the manufacturing processes. If the oil is extracted by pressing method, the percentage of fat ranges between 14.5 and 23%; however, if organic solvents are used (Fig. 2), the percentage decreases. The oil content of the resulting material is 5%. Furthermore, OMP supplementation increases the levels of monounsaturated fatty acids (MUFAs) and decreases that of saturated fatty acids (SFAs) in the milk and meat of ruminants with beneficial effects for consumers' health (Tzamaloukas *et al.* 2021). OMP contains a significant amount of metabolic energy, but the degree to which this energy is utilized by the animal is usually reduced due to the high percentage of crude fiber in this substance (57%) (Al-Jassim *et al.* 1997). In terms of minerals, OMP is a good source of calcium. It does, however, contain trace amounts of phosphorous, magnesium, and sodium (see Table 2 for lists the chemical composition of OMP).

The addition of OMP to the rations was based on successful trials and experiments that showed a positive effect on performance and/or feed costs. In summary, numerous efforts have been made to improve the nutritional value of OMP in order to increase its use in animal diets, chemical and biological treatments. Despite the fact that OMP as a feed source additive may improve livestock production, there are a few drawbacks. The first is that OMP, due to its relatively high water content and the still large amount of oil it retains, becomes rancid and unfit for animal consumption when exposed to air. Another issue is the need to remove toxins and tannins from PMO before using it as a feed supplement. According to this review, we will only look at the benefits of using OMP as feed for each species of livestock based on recently published scientific articles. In fact, it has inspired a business that collects and processes olive waste using advanced technology and converts it into animal feed.

The OMP as a feed in dairy cattle studies is scarce and shows different feedback with variable results due to different methods of producing OPM (*e.g*., processing and pressing as wet or dehydrated or absence or presence of stone) (Castellani *et al.* 2017; Vargas-Bello-Pérez *et al.* 2018). In general, a supplementation level of 5–20% had no effect on milk yield. The OMP diet had a significant impact on milk protein content. In details, reasonable results were obtained when OMP was added to the total diet at a 15–17% level. In comparison to the control treatment, this addition level increased the ether extract by approximately 60–65%. Nonetheless, it was reported that using 15% OMP in the diet of cattle, buffaloes, goats, sheep, and camels resulted in a 65% increase in ether extract (Fayed *et al.* 2001; Terramoccia *et al.* 2013; Chaves *et al.* 2021). As a result, it is advised to feed OMP to dairy animals when they require energy. For example, it is well understood that energy balance in dairy cows is achieved by energy intake to meet their daily requirements for various functions during the early lactation stage. The OMP, on the other hand, altered the fatty acid profile of milk. When OPM was used as a feed, Castellani *et al.* (2017) found an increase in conjugated linoleic acid, a decrease in short- and medium-chain fatty acid, and no difference in polyunsaturated fatty acid levels. In the beef industry, OMP showed promise as a supplementary feed. In addition, OMP inclusions at 15% reduced meat cooking loss and shear force value (Chiofalo *et al.* 2020), whereas OMP inclusion at 4.8% had no effect on growth performance, carcass traits, or meat sensory attributes (Castro *et al.* 2016). The OMP improved the nutritional value, texture, tenderness, and digestibility of produced meat; particularly for breeds such as Wagyu cattle (Japanese breed). Dunne (2019) also reported that the high fat marbling in Wagyu meat contributes to a lower melting point.

Supplementing OMP had a positive effect on the ratio of saturated to unsaturated fatty acids. It was reported that OMP feed improves meat flavor and increasing tenderness as well. Studies showed an increase of 50 and 100% in glutamic acid and carnosine, respectively, reflecting nutritional benefits and significantly taste corresponding to the flavour of glutamates. Such notable results were reported in the high-end Wagyu beef cattle breed of Japan. When fed at 20% as a destoned olive cake of the dietary ration, the OMP as feed for fattening sheep and goats (lambs and kids) showed a significant difference in body weight, growth rate, and feed conversion ratio (Sadeghi *et al.* 2009). Because it is a low-cost byproduct, OMP can be used as an alternative feed source for lambs at a rate of 20–30% without affecting their growth performance or carcass traits (Christodoulou *et al.* 2008; Alkhtib *et al.* 2021).

Finally, due to its low protein and high fiber contents, OMP is still limited as a feed for poultry, primarily layer and broiler chickens. In general, the findings of various studies showed that including up to 10% OMP in the diet of broiler chickens and commercial laying hens has no negative effects on the birds' performance and improves meat quality (Saleh and Alzawqari 2021). Furthermore, when up to 9% OMP is included in diets, egg weight and yolk index increase (Oliveira *et al.* 2021). The OMP can also change the lipid profile of chicken meat and egg yolk, increase the amount of monounsaturated fatty acids while decrease the amount of saturated fatty acids. Broiler gut microbiota has higher antibody titers for infectious bronchitis and gumboro diseases (Oliveira *et al.* 2021).

Conclusions and Perspectives

It is concluded that when composting OMP, natural organic residues such as manure, straw, olive twigs, and leaves should be added to allow them to decompose in aerated piles. Compost from OMP contains enough nutrients without containing any harmful heavy metals, and it affects the hydraulic conductivity, infiltration, and water holding capacity of the soil in various ways depending on the soil texture and structure. As a result, we recommend using OMP as compost while taking into account the environmental consequences on soil and water, as it can be a high-quality soil fertilizer. Furthermore, many of the compounds found in OMP could be a promising option for pest control in the Mediterranean region, but more field research is needed to assess its effects on specific pest problems in specific cropping systems. The use of OMP composts as biodegradable pesticides may have many applications in organic agriculture. The development of a sustainable pest control strategy based on the use of OMP composts in order to reduce the use of synthetic pesticides may have significant economic benefits. More research is needed in this context to investigate the feasibility of incorporating OMP into large-scale pest management programs. Furthermore, considering OMP as animal feed resulted in increased revenue and the potential for tasty meat and healthy milk. Because it is a cheap by-product, OMP can be used as an alternative feed source for livestock up to 20% for ruminants and 10% for poultry without affecting their performance viability. It can be concluded that it is a primary solution for the elimination of OMP waste and the associated environmental and economic issues. Additional research is needed to assess the long-term impact of uncontrolled OMP disposal in agricultural land, as well as the risk of soil and water contamination. In addition, since all the studies on OMP were conducted on controlling diseases, nematodes and weed pests, future studies should be done to test its efficacy against insect pests. Furthermore, future research should be focused on how feeding livestock by op could affect animal biodiversity and/or growth traits.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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