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Review

Organic Fertilization and Tree Orchards

Theocharis Chatzistathis [1,*], Victor Kavvadias [2], Thomas Sotiropoulos [3] and Ioannis E. Papadakis [4]

1 Hellenic Agricultural Organization (ELGO) 'DIMITRA', Institute of Soil and Water Resources, 57001 Thessaloniki (Thermi), Greece
2 Hellenic Agricultural Organization (ELGO) 'DIMITRA', Department of Soil Science, Institute of Soil and Water Resources, 14123 Athens (Lycovrisi), Greece; v.kavvadias@swri.gr
3 Hellenic Agricultural Organization (ELGO) 'DIMITRA', Department of Deciduous Fruit Trees, Institute of Plant Breeeding and Genetic Resources, 59035 Naoussa, Greece; thosotir@otenet.gr
4 Laboratory of Pomology, Agricultural University of Athens, Iera Odos 75, 11855 Athens, Greece; papadakis@aua.gr
* Correspondence: t.chatzistathis@swri.gr

Abstract: Organic fertilization has been proposed as an alternative approach to supply nutrients for crops, in the frame of organic and sustainable agriculture, with the aim to decrease high inorganic fertilization rates, protect the environment and decrease production costs for farmers. Since different types of organic fertilizers, such as manures, olive mill wastewater (OMW), sewage sludge (SS), crushed pruning wastes, composts and cover crops, exist as soil amendments to improve soil fertility, enhance plant nutrition and sustain the productivity of tree crops, their role as biofertilizers has been fully analyzed under the most important published papers. In addition, the benefits and drawbacks of organic fertilization, in a comparative approach with inorganic fertilization, are presented and discussed. Within the most important advantages of organic fertilizers, the enhancement of beneficial soil microorganisms and the improvement in soil physical properties and fertility should be included, while their most important disadvantage is their inability to directly satisfy the prompt N nutritional needs of tree crops, due to slow N mineralization rates. Finally, some novel aspects on the interrelation among innovative organic fertilizers for tree crops, sustainable field management, crop productivity and fruit quality are also included in this review, under the light of the most important and recent research data existing in the literature, with the aim to provide recommendations and future directions for organic fertilizers by tree growers.

Keywords: biofertilizers; manures; olive mill wastewater (OMW); sewage sludge; composts; cover crops

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1. Introduction

One of the most promising challenges for modern sustainable agriculture is how to decrease the high unnecessary fertilization rates without (i) negatively influencing the nutritional requirements of plants, and (ii) decreasing crop yields and plant products' quality. More specifically, the excessive use of inorganic fertilizers has led to the deterioration of soil quality (e.g., increased salinity or acidification), surface and groundwater pollution and increased greenhouse gas emissions [1]. Apart from the above-mentioned effects of the excessive use of inorganic fertilizers on soil chemistry and some environmental aspects related to climate change, the decreased activity of microorganisms should not be neglected from the negative consequences on soil quality. Thus, the large consumption and high cost of inorganic fertilizers, together with their negative environmental impact, necessitate the use of alternative nutrient sources, in order to reduce the demand for inorganic fertilizers [2].

Under these conditions, the use of organic soil amendments for fertilization seems to be the unique solution for crop nutrition. Low N use efficiency by crops due to high N fertilization rates has been studied; Carranca et al. (2018) [3] found that N use efficiency by young and mature fruit trees is lower than 55%, and losses of N fertilizers may occur, with consequent economic and environmental concerns. It was also found that the highest N use efficiency (NUE) in a wheat–corn cropping system, fertilized for 15 years either with manure or with chemical fertilizers' inputs, occurred in the manure treatment [4]. Alternative organic and mineral N fertilizers, such as manure application, composts, mulching and cover crops, have scarcely been used in perennial fruit trees, despite the fact that society's expectations call for more sustainable production, and demand for organic fruit production is increasing [3]. Thus, according to our opinion, organic fertilization and management practices are needed in the near future to sustain fruit crop yields, enhance soil fertility and satisfy trees' nutritional demands.

Apart from the ability of organic amendments/fertilizers to decrease inorganic N inputs and enhance the sustainability of agroecosystems towards more sustainable production of fruits, it is also stated that their application enhances soil nutrient availability and increases organic matter contents and microbial biomass, while it also stimulates microbial activity, field productivity and fruit weight [5–9]. Another very important aspect of organic amendments' application is that they may improve food quality; incorporation of vermicompost in the soil had a significant impact on the antioxidant and antibacterial properties of *C. cajan* leaves, while farmyard manure application resulted in a high concentration of total phenols and chlorophyll [10]. Furthermore, the application of a two-phase olive mill waste (OMW) compost in an olive grove led to a 15% higher olive oil content, compared to inorganic fertilization [6].

Among some of the most important and commonly used biofertilizers to satisfy the nutritional needs of tree crops, decrease inorganic fertilization inputs and boost the sustainability of agroecosystems are the different types of manures [11], composts derived from municipal wastes with other vegetal (e.g., pruning) materials [12,13], sewage sludge [14], crushed pruning wastes [15], by-products of the agricultural sector (e.g., olive mill wastewater (OMW)) [5,9,16], microbial fertilizers [17] and the use of cover crops, in co-cultivation with fruit trees [18].

Based on the most important and recent literature data on organic fertilization for tree crop nutrition, the aims of this review are the following: (a) to indicate the beneficial effects of organic fertilization on soil fertility, organic C and soil microbiology, (b) to present and compare the positive and negative aspects of organic and inorganic fertilizers on trees' nutrition and field sustainability, (c) to point out the importance of organic fertilization on tree productivity and fruit quality, (d) to present the current situation of organic fertilization and to share thoughts about its future perspectives, realizing this in relation to the presentation of innovative and alternative organic soil amendments used as biofertilizers, and (e) to categorize the different types of organic amendments (manures, composts, by-products of the agricultural sector, sewage sludge, crushed pruning wastes, cover crops) that are used—or could be used—as biofertilizers and showcase their importance for tree crop nutrition.

2. Benefits and Drawbacks of Inorganic Fertilization

Within the most important drawbacks of inorganic fertilizers, the fact that, for their production, non-renewable sources are used should be included. In addition, overuse of inorganic fertilizers can result in high nutrient leaching, and surface and underground water pollution [19], leading to eutrophication in aquatic systems [20], and soil acidification and salinization [21], as well as regeneration of greenhouse gases [22,23]. Repeated and excessive use of chemical fertilizers (e.g., triple superphosphates) may result in accumulation of heavy metals in soils (arsenic, cadmium) and crops [24]. Moreover, excessive use of chemical fertilizers may (i) have a detrimental effect on soil decomposer organisms, (ii) reduce mycorrhiza colonization and (iii) inhibit symbiotic N fixation due to excessive N fertilization [25,26]. Nutrients provided by inorganic fertilizers can be washed away easily due to excessive irrigation. Approximately up to 50% of N and 90% of P have been reported to run off from crop fields [22,27]. Application of inorganic fertilizers does not improve soil fertility in the long term because large amounts of organic matter and nutrients are removed every crop season from the fields after harvesting [28].

On the other hand, inorganic fertilizers can immediately supply crops with the necessary quantities of nutrients (especially with those of N), and thus the nutritional requirements of crops may be promptly satisfied, something which cannot be achieved with the use of organic fertilizers, acting as slow-nutrient release fertilizers, usually unable to meet the prompt nutritional requirements of crops. The high organic C inputs (combined with the low organic N concentration of many organic residues) in the soil after organic amendments' application may increase the ratio of C/N up to 50 [29]; under such imbalanced C/N values, the N mineralization rate is decreased, since N is required for bacteria [30]. Apart from the above benefits of inorganic fertilization, chemical fertilizers have a standard elemental and nutrient composition (types and chemical forms of nutrients), while the organic ones have an unstable nutrient composition; therefore, it is easier for producers to calculate and accurately determine the exact quantities of nutrients' inputs after inorganic fertilization.

Fertilization with synthetic fertilizers is less expensive than that with organic fertilizers; thus, production costs are, in most cases, lower in inorganically fertilized crops. Finally, despite the better economic viability of farms fertilized with synthetic fertilizers, inorganic fertilization cannot improve soil physical properties, organic matter content and health, while, in contrast, organic fertilizers may significantly contribute to the improvement in these soil variables [24–30].

3. Benefits and Drawbacks of Organic Fertilization

Organic fertilization has a significant impact on the enhancement of soil organic C, cation exchange capacity (C.E.C.) and microbial activity, i.e., it plays a crucial role in improving soil health, properties and promoting the sustainability of agroecosystems [7,9,31–35]. It was also found to improve soil physical properties, such as soil bulk density, to optimize porosity, to increase soil water storage and to restore degraded (arid) soils [34]. Thus, the first main ('key') step of the beneficial role of organic fertilization is the enhancement of soil organic matter, which, afterwards, contributes to improved soil health (microbial activity) and physical properties. Then, improved soil properties represent the second step towards restoring degraded soils [9,34]. The application of organic fertilizers may alleviate aridity (low fertility) stress and enhance the photosynthetic rate of plants [36].

However, organic fertilization does not provide direct (prompt) effects on the enhancement of soil fertility and satisfaction of the nutritional needs (especially those of N) of crops. The drawback of the non-prompt response of plants to organic fertilization (due to the slow mineralization rate of N) may be solved, in many cases, by supplying organic N, which may be complementary to inorganic fertilization [37]. Composted manure is insufficient for crop fertilization; this is why the co-application of composted manure with inorganic fertilizers has been recommended as the optimum strategy to improve the soil organic C content and soil properties in croplands [38]. In addition, the increased soil aridity (due to soil degradation provoked by unbalanced fertilization for many years) could be also faced via co-application of composted manure with inorganic fertilizers, something which improved apple orchards' yields [34].

Another problem related to the high application rates of some by-products of agricultural/industrial production is the toxicity risk for soil fauna and some biologically mediated processes [39], due to high polyphenol concentrations, heavy metal accumulation and high Cl^- and SO_4^{2-} concentrations, as well as elevated electrical conductivity [5,9,40,41]; in addition, depressed growth and phytotoxicity problems have also been reported due to high application rates of these by-products, especially OMW [41,42]. Apart from the chemical composition (polyphenols, metal accumulation) of agricultural by-products which could be responsible for the toxicity effects on some soil biological processes, high application rates may also be responsible for toxicity risks [39]; this is why high application rates of these by-products should be avoided.

In addition to the above, organically fertilized orchards have a higher production cost; thus, in cases where the higher production cost cannot be counterbalanced by the achievement of a higher fruit quality and better market prices, organic fertilization fails to support economic viability. In addition, it is often difficult for producers to find sufficient quantities of organic fertilizers in order to successfully satisfy the nutritional requirements of crops. However, high manure quantities may be easily found in cases where growers combine crop production with domestic animal breeding; thus, these mixed systems of organic crop production (i.e., crops fertilized with manures) with animal breeding are of high socioeconomic importance only in specific rural areas [31].

Perez-Romero et al. (2017) [43], who studied carbohydrate and N reserves in two cultivars of Japanese plum grown under organic and conventional management, stated that similar carbohydrate and N levels were found between the plants grown under inorganic and organic fertilization; in contrast, the two cultivars of Japanese plum studied exhibited both delayed flowering and premature defoliation under organic management [43].

4. Inorganic or Organic Fertilization for Tree Crops?

Insignificant differences have frequently been stated between inorganic and organic fertilizers' application on plant growth, crop yields and tree productivity [7,11], while in some other cases, more promising results on plant nutrition and growth were obtained with organic fertilization [44,45]. After 5 years of soil application with a suitable compost (consisting of sheep manure and wheat straw), higher productivity (21.4%) of a *Prunus salinica* orchard, a greater fruit diameter (7.8%) and a heavier fruit weight (22.4%) were obtained, compared to the control plots (no compost application). In contrast, insignificant differences in foliar nutrition were found between the amended and control plots [8]. Thus, organic fertilization is not a limiting factor in achieving optimum foliar nutrition, sufficient tree biomass and satisfactory crop yields. The response of Šampion apple trees to different organic mulches (barley straw, chipped pine bark, forest humus, compost, cow manure, commercial peat moss and commercial mycorrhizal substrate) was studied; it was found that the highest number of fruits was produced by trees grown on the forest humus mulch, while the forest humus, compost and cow manure mulches had a beneficial effect on the content of mineral elements in the soil and leaves of Šampion apple trees [46].

In a comparative study between long-term inorganic and organic fertilization on soil dissolved organic C (DOC), and its correlation with maize yields, it was found that, from the perspective of soil DOC, organic manure application could be the most suitable fertilization practice for the acidic Ultisols of southern China [47]. Zhu et al. (2015) [48] also found that in a rice–wheat rotation system, in addition to the total SOC, the content of DOC also significantly affected crop yields. In some other studies, it was concluded that compared to SOC, DOC is more sensitive to agricultural practices, such as fertilization strategies [49,50]. From an agronomic point of view, this is of great importance, since by boosting SOC and DOC (via long-term applications of organic fertilizers), crop yields may be enhanced.

Apart from the positive effects of organic fertilization on soil organic C, organic amendments were also found to increase the abundance of beneficial soil microorganisms and decrease the relative abundance of plant pathogenic fungi (including *Fusarium*) in *Actinidia sinensis* orchards [51]. Thus, organic fertilization provides a 'wall' of protection against pathogenic fungi, protecting root health from harmful fungi attacks; this root protection may be achieved via antagonism between soil microbial taxa (especially between plant growth-promoting (PGPR) bacteria and pathogenic fungi) [51]. It was found that a decrease in rhizosphere microbial diversity was responsible for the development of soil-borne diseases in plants. The abundance of beneficial microorganisms (e.g., PGPR bacteria, actinomycetes and some fungi genera) was not only found to differ between inorganic and organic fertilized soils but also among different organic soil amendments [52]; Masunga et al. (2016) [53] found that bacteria (Gram-positive and Gram-negative), actinomycetes and fungi were more abundant in clover-amended soils than in soils amended with manure or composts.

Despite the positive effects of organic fertilizers on organic C, soil physical properties, fertility, trees' nutrition and crop yields, there are enough studies supporting the idea that the most realistic solution to satisfy the nutritional needs (especially those of N) of tree crops without a negative influence on vegetative growth and yields is combined fertilization (co-application of organic and inorganic fertilizers). It was found that the co-application of cattle manure with inorganic fertilizers (NPK 15-15-15) and natural zeolites not only induced a decrease in soil acidity but also improved the humus content, total N and available P and K levels [54]. Similarly, it was concluded that biochar made from different feedstocks (baby corn peel biochar, branches of mango tree biochar, rice husk biochar), in combination with NPK fertilizers' application, was the optimum solution to improve soil fertility and soil enzymatic activities, also allowing reduced fertilizer application and food production costs in cowpea grown in an acid soil [55]. In contrast, Roussos et al. (2017) [35] found that the yield of 'Koroneiki' olive trees under organic fertilizers' application was approximately 55% higher compared to that achieved by the use of inorganic fertilizers. Similarly, according to the same authors, a higher C assimilation rate was achieved under organic fertilizers' application.

From all of the above, it can be concluded that the combination of inorganic and organic fertilizers results in greater benefits than either input alone, due to the positive interactions with soil physicochemical and biological properties [28]. Thus, integrated fertilization management (combination of minerals with organic fertilizers) has been shown to contribute to enhanced fertilizer use efficiency, maximize crop yields and sustain healthy soils, with a higher ability for soil carbon sequestration [26,56,57].

5. The Importance of Organic Fertilization for Fruit Tree Crops

5.1. Organic Fertilization and Productivity of Tree Crops

There are enough studies supporting that tree growth and field productivity were positively influenced by organic fertilization [8,37,42,46,51,58], which shows the beneficial role of organic soil amendments to boost tree biomass and yields, probably via improved soil fertility and plant nutrition. Indeed, in many published data, it was found that nutrient uptake and foliar nutrition under organic fertilization were similar to those obtained with inorganic (conventional) fertilization [7,11], and even more promising results were obtained in the first case [44,45]. Since nutrient availability is within the most important and crucial factors determining plant growth and productivity (together with soil moisture, temperature and solar radiation) [59], it is quite reasonable to assume that, under the same environmental conditions, similar, or even better, results on plant nutrition can be obtained with organic fertilizers than with inorganic ones, leading to similar or higher plant biomass and tree productivity. In a comparative study between intensive conventional mono-cropping in fruit orchards and crop diversification, conservation tillage and organic fertilization, it was found that no significant effect was observed in tree crop yields due to organic fertilization [60], which shows that organic soil amendments can produce similar beneficial effects on tree productivity to inorganic fertilizers.

Long-term fertilization might improve the productivity of kiwifruit orchards, by increasing rhizosphere microbial diversity and the relative abundance of plant growth-promoting bacteria in the rhizosphere of kiwifruit plants, which clearly shows the beneficial role of soil microorganisms in boosting crop productivity [51]. Similarly, it was found that an improvement in the composition of rhizosphere microbial communities can promote the growth of strawberry seedlings [61].

Marron et al. (2015), who performed a literature review on the land application of organic residues in short-rotation tree plantations, stated that, among these amendments, manures, composts, sewage sludge and wastewater seem the most effective in stimulating tree growth; in contrast, ashes have less impact on boosting plant growth [42]. Finally, apart from the tree growth stimulation activity of organic biofertilizers, there are studies which have concluded that some organic fertilizers used as biostimulants (such as seaweed extracts) may be useful tools to moderate the negative effects of alternate bearing in apple orchards [62].

During a period of 10 years, the response of the growth and productivity of the peach cultivars 'Springtime' and 'Redhaven' to N, P and K fertilization and manure application was studied. The following fertilizer combinations were adopted: control (no fertilization), N, P, K, NP, NK, PK, NPK, cattle manure, N + manure, P + manure, K + manure, NP + manure, NK + manure, PK + manure, NPK + manure. Application of N + manure to peach trees of the cv. 'Springtime' resulted in the highest productivity. The highest productivity of the cv. 'Redhaven' was recorded in the treatments of N and NPK. Fruit set of the cvs. 'Springtime' and 'Redhaven' was highest in the NP + manure treatment, and PK + manure, NK + manure and K treatments, respectively [63].

5.2. Organic Fertilization and Fruit Quality

For fig trees (*Ficus carica* L.), it was found that the highest levels of organic fertilizers provided the best results for both yields and fruit quality [37]. During a period of 10 years, the response of the fruit quality of the peach cultivars 'Springtime' and 'Redhaven' to N, P and K fertilization and manure was studied. The following fertilizer combinations were adopted: control (no fertilization), N, P, K, NP, NK, PK, NPK, cattle manure, N + manure, P + manure, K + manure, NP + manure, NK + manure, PK + manure, NPK + manure. From this study's results, it was concluded that the total soluble solids content (%) of fruits of the cv. 'Springtime' was not significantly altered, in comparison to the control, for all the treatments used. The mean fruit weight of the cv. 'Springtime' was higher in the NP, NPK, NP + manure and NPK + manure treatments, in comparison to the P treatment. Finally, the mean fruit weight of the cv. 'Redhaven' was the highest in the NP + manure treatment [64]. Application of a commercial fertilizer from municipal waste composts in kiwifruit and cherry orchards in 2020 showed an increase in total soluble solids and an improvement in color in cherry trees; in addition, an increase in total soluble solids in kiwifruits, compared to inorganic fertilization, was observed (Sotiropoulos, unpublished data). However, the experiment is being repeated during the current growing season.

It was found that, after long-term application of organic fertilizers in kiwi orchards (*Actinidia chinensis*), the relative abundance of potentially beneficial microorganisms was positively correlated not only with fruit yield but also with fruit quality [51]. Tree growth, productivity, fruit quality attributes and antioxidant activity were tested in the apple cultivar 'Idared' under different fertilization treatments [65]. Fertilizer regimes had a significant effect on the fruit weight and flesh firmness, but their effects on the fruit size and dimension ratio were non-significant. The effects of the sheep manure application rate (i.e., 13, 26 and 39 kg tree^{-1}) and application method on the growth, fruiting and fruit quality of Balady guava trees were studied by El Gammal and Salama (2016) [66]. The results showed that by increasing the sheep manure application rate, a progressive enhancement of the studied fruit growth quality traits (fruit weight, total sugars, total soluble solids) was obtained [66].

Based on these data, we believe that, within the next few years, fruit quality will become a crucial issue for consumers, asking for safe, healthy, high-nutritional quality agricultural products, with minimal or no adverse impacts on the environment [62], also creating new market opportunities and ensuring higher incomes for producers. Since organic fertilization, together with sustainable irrigation management, is within the primary factors affecting the achievement of a high fruit quality in orchards, it is estimated that the beneficial role of innovative organic fertilizers, often enriched with beneficial soil microorganisms, in achieving a high fruit quality will attract the interest of many researchers to better clarify the plant physiological mechanisms affecting the qualitative nutritional characteristics of fruits. In addition, for the production of organic fertilizers, the increased interest of consumers for high-quality organic fruits means more demand for innovative organic fertilizers, offering new job opportunities for young researchers.

6. The Future of Organic Fertilization for Tree Crops, in Relation to Innovative and Alternative Organic Soil Amendments Used as Biofertilizers and Sustainable Field Management Practices

Since not only tree crop yields but also fruit quality may be ameliorated with organic fertilization, and there is an increasing interest for certified organic (biological) products by consumers [37], it is estimated that within the next few years, achieving a high organic fruit quality will play a more crucial role in market opportunities, since certified organic products will achieve higher prices.

In addition, the public opinion during recent years has become more and more sensible, stating that agriculture is not only appointed to produce food but also, due to its potential, to provide a range of ecosystem services, depending on the management options adopted at the field scale [67]. In these cases, the role of organic C is crucial; within the most important field management practices to enhance soil organic C, improve soil properties and boost related functions (e.g., supply of nutrients, water storage) are the following: tillage/no-tillage, cover crops, retention/burning of pruning residues and mineral/organic fertilization [67]. Similarly, in the study of Morugan-Coronado et al. (2020), who investigated the benefits of crop diversification, conservation tillage and organic fertilization as alternatives to intensive conventional mono-cropping, it was found that all the diversified systems, conservation tillage and organic fertilizers induced positive effects on soil organic C, fertility and quality [60]. Thus, it is estimated that, within the next few years, in order to boost ecosystem services in fruit orchards, more sustainable practices at the field scale will be adopted by farmers; in this frame, the role of organic fertilization will become more and more important (since enhancement of organic C is the first most crucial step towards shifting from conventional to organic and sustainable agriculture, and providing ecosystem services). Figure 1 shows the categories/types of organic fertilizers that can be used for the enhancement of the productivity of tree crops; according to our opinion, most of them will play a crucial role towards boosting tree crop yields and partially substituting inorganic fertilizers (in order to decrease high fertilization rates).

6.1. Olive Mill Wastewater (OMW) and Other By-Products of Agricultural/Industrial/Food Production That Can Be Used as Biofertilizers for Tree Crops

Olive mill industry waste produces millions of m^3 per year; solid wastes are known as pomace (skins, pulp, seeds and stems of the fruit), while liquid wastes are known as olive mill wastewater (OMW). OMW is characterized as acidic (pH 3.5–5.5), with a chemical oxygen demand (COD) of up to 220 g/L, biochemical oxygen demand (BOD) content of up to 120 g/L and a high concentration of suspended solids (7–15 g/L) and phenolic compounds of up to 25 g/L, with several inorganic constituents [68].

Many studies showed a positive effect of OMW application on the physical, chemical and microbiological properties of agricultural soils [5,9,69]. Furthermore, OMW's application enhances soil enzyme activities [69,70], increases soil moisture (thus decreasing the irrigational needs of crops) [9] and positively affects tree vegetative activity and crop yields [5,16,69]. In particular, the high K concentration of OMW (which is owed to the fact that it is the most abundant nutrient in olive fruits) causes the absorption of K in large amounts by olive trees [71]. However, OMW spreading on soils is still subjected to high controversy between its fertilization properties and negative effects on soil fertility, due to (i) its high acidity and salinity, and (ii) the high content of potentially phytotoxic compounds, such as phenols.

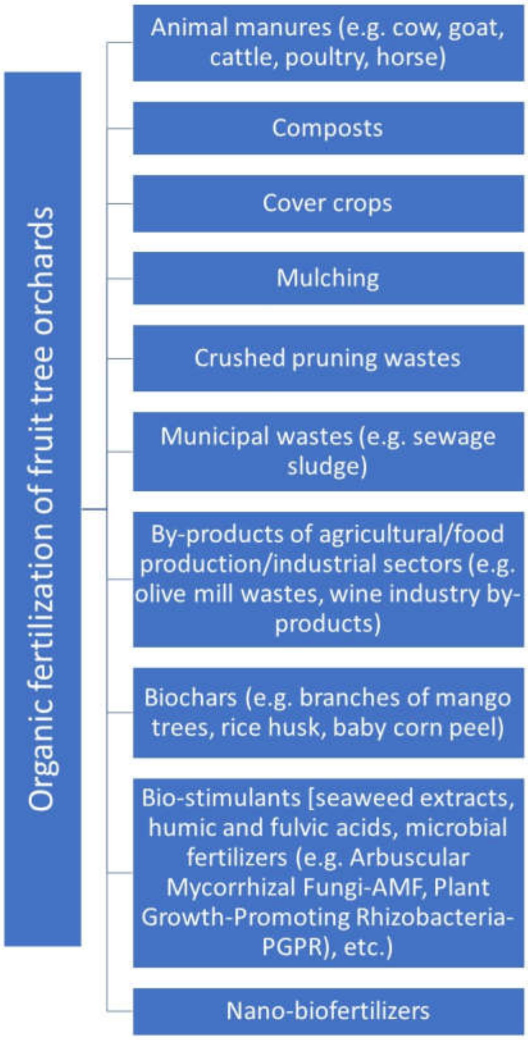

Figure 1. Categories/types of organic fertilizers for tree crops.

In fact, the uncontrolled disposal of OMW is a significant environmental problem for the Mediterranean countries [72]. The uncontrolled and long-term disposal of raw OMW in unprotected evaporation ponds, or directly onto soil, increased salinity, toxicity to plants and soil microorganisms and contamination of surface and groundwater [72,73]. One of the main negative issues provoking concern about the use of OMW is its high phenolic content [5,72], which may cause phytotoxicity [9,74]. Other negative impacts of OMW's field application on soils may be the enhanced electrical conductivity, as well as the increase in metal accumulation [75] and Cl^{-}, SO_4^{-}, PO_4^{3-} and NH_4^{+} concentrations [72]. Under these circumstances, the application rate of OMW in soils plays a crucial role in order to avoid negative impacts; Vella et al., (2016) [76], who studied the effects of untreated (raw) OMW spreading on soil properties, stated that application rates of about 30 m^3 ha^{-1} $year^{-1}$ (significantly lower than 80 m^3 ha^{-1} $year^{-1}$ established as the maximum limit by the Italian law), even if repeated for many years, had little impact on pH, electrical conductivity, organic matter and polyphenol content. Other researchers suggested that pre-treatment of OMW before land application is needed, in order to decrease its high phenol content [77]; such type of pre-treatment may be targeted towards decreasing its high phenolic content (or producing dephenolized OMW) [73] and degrading the chemical oxygen demand (COD) [77,78]. Another simple method to reduce the high phenol content of OMW is its dilution with water, at a ratio 1:3 (25% OMW:75% water), in order to eliminate phytotoxicity [79]. Table 1 shows the chemical characteristics of untreated (raw) OMW. From all the above, it may be concluded that further and detailed studies are needed in order to assess the short- and long-term effects on soil properties, and, subsequently, on surface water and groundwater, as well as determining the optimum OMW application rates for specific soil and climatic conditions [72].

Table 1. Range of chemical properties of untreated (raw) olive mill wastewater (OMW) (from Ayoub et al., 2014; Vella et al., 2016) [32,76].

Chemical Parameter of OMW		Nutrient Concentration of OMW		Nutrient Concentration of OMW	
pH	4.91–5.42	Polyphenols (mg L^{-1})	960–2269	Fe (mg L^{-1})	24–38.2
EC (dS m^{-1})	7.64	Total N (g L^{-1})	0.54–1.04	Zn (mg L^{-1})	1.89–5.8
Total solids (g L^{-1})	69.83	Total P (g L^{-1})	0.24	Cu (mg L^{-1})	1.33 ± 0.07
Water	95%	K (g L^{-1})	2.78–5.9	Na (g L^{-1})	0.06–0.97
COD (g L^{-1})	58.6–92.4	Ca (g L^{-1})	0.29–0.72	Cl (g L^{-1})	0.50
BOD_5 (g L^{-1})	27–36.3	Mg (g L^{-1})	0.23–0.37	Pb (mg L^{-1})	<0.09–0.27

In recent decades, organic matter in agricultural soils has significantly declined due to unsustainable management practices and climate change, leading to soils with increased erosion and degradation. The high organic C of OMW may offer an excellent solution, via its application in soils, to restoring degraded croplands (e.g., eroded soils, or soils suffering from a low organic matter content due to unsustainable management practices), since one of the first steps in land restoration should be the enhancement of low organic C levels [9].

Most of the published studies on OMW were focused on olive groves [5,16,69,70,80], while the rest referred to annual crops [81,82]. Independent of the type of crops (annual or perennial) which were focused on in the published studies, most of them concluded that OMW is (i) an inexpensive source of nutrients that could partially replace inorganic fertilizers and decrease their high inputs in agroecosystems [9,76], as well as (ii) a non-negligible water source [40,72].

Besides OMW, one of the by-products of industrial production that could be used as an organic amendment is pine chip gasifier biochar (obtained from industrial gasification facilities); gasifier pine biochar (considered, until recently, as waste) is a C-rich material, which could be useful as a soil amendment. However, biochar treatments did not show any significant effect on soil microbial biomass and barley crop parameters, while soil fauna activity was negatively impacted by gasifier biochar [39]. According to the same authors, the unique positive effect of gasifier biochar was the boost in soil K. Other types of biochar studied as organic soil amendments were those derived from (i) baby corn peel, (ii) branches of mango trees and (iii) rice husk. Compared to the results of Marks et al., (2016) [39] for gasifier biochar, the data for the three above-mentioned types of biochar were more promising, since they induced a higher activity of enzymes related to the P cycle, and higher cowpea yields [55]. It was found that application of woody biochar and woody mulch was successful in mitigating nitrous oxide (N_2O) emissions from a poultry litter-amended soil [83].

Finally, in addition to OMW and biochar, microbial fertilizers (MFs) constitute an emerging class of organic fertilizers, consisting of dried microbial biomass produced on effluents from the food and beverage industry [17]; MFs have the potential to contribute to (i) sustainable plant nutrition, performing as good as a commercially available organic fertilizer, and (ii) circular economy strategies [17].

6.2. Animal Manures

Different types of manure (e.g., cow, goat, poultry, sheep, horse, pig manure) may be used as organic soil amendments to enhance soil fertility for crops [84]. However, the different types of manure significantly differ in their nutrient content (Table 2); thus, their use as enhancers of soil fertility and supporters of crop nutrition should be seriously taken into consideration by tree growers before field application [11]. The nutrient content of manures depends not only on the type of animal but also on animal feeding and manure preservation [85]. In comparative studies between manure application and inorganic fertilization treatments, manures (as organic fertilizers) provided similar, or even better, results (with regard to crop yields, trees' nutrition and soil fertility) to those produced by conventional (inorganic) fertilizers [7,11,44]. It was stated that the growth, yield and nutritional composition of *Moringa oleifera* in sandy soils could be ameliorated through a combined application of organic fertilization (chicken or farmyard manure) and a proper Co dose [86]. In some other cases, the enhanced photosynthetic capacity of apple trees was found to elevate apple tree yields by 8.8% and 13.3% under low and high composted manure applications, respectively, in orchards of the Loess Plateau, China [34].

Table 2. Nutrient composition of different manures (from Therios, 1996) [85].

Type of Manure	N	P % d.w.	K
Poultry manure	1.56	0.40	0.35
Sheep manure	1.40	0.21	1.00
Horse manure	0.68	0.10	0.60
Pig manure	0.50	0.14	0.38

Besides the impact evaluation of manure on crop yields and productivity, among the main questions still remaining unanswered is the combined agronomic and economic evaluation of animal wastes' application on tree crops. Poultry sludge application (at a rate of 400 g tree^{-1} N) had the lowest cost and was determined as the most appropriate nutrient proportion for fertilization practices in *Juglans regia* L. plantations grown on marginal soils; in addition, the use of poultry manure resulted in approximately 65.4% savings, in terms of present value evaluation [87]. From the relative inadequacy of the data existing in the literature on the economic evaluation of animal manure application, it is clear that more emphasis should be placed on this topic by researchers in their future studies.

Livestock manure can be applied as raw or composted [88]. The most used animal manures are those that come from original substrates from swine, poultry, cow or horse manure [89]. The low pH of farmyard manure reduced the pH of alkaline soils [90], while manuring improved the soil porosity and water holding capacity [91].

Goldberg et al., (2020) [92] suggested that, prior to the assimilation of organic matter into the soil, manure application could have adverse effects on seed germination and crops by increasing salinity, and on the soil structure by sodicity. The authors investigated the short-term effects of animal manure application on soil structure stability, infiltration rate, runoff and soil erosion formation under rainfall conditions. They reported that the manure reduced the soil structure stability, reduced infiltration, increased surface runoff and led to soil loss, indicating the high sensitivity of arable soils to erosion processes during the first few weeks following the addition of manure to the soil. In addition, manure slowly releases essential soil micro- and macronutrients over time. Manures reduced the concentration of residual macro- and micronutrients in the soil [93], while manuring combined with fertilization contributed to nutrient transformations in the soil, as well as modifications in the particle density, porosity and water holding capacity.

Manure addition caused a modification of the soil bacterial community structure [94]. Furthermore, manures' application enhanced microbial respiration, enzymatic activities and nitrogen mineralization rates [95]. It was demonstrated that applying manure is invaluable for improving soil fertility, by increasing the population of microorganisms which are useful for nutrient transformations in the soil [96]. On the other hand, the overuse of animal manure can release pathogens and other dangerous chemical compounds [97]. The presence of a variety of human pathogens in soils amended by poultry manure could menace humans consuming the infected plant food or water [94].

In conclusion, manures reduce the need for chemical fertilizers. It was found that the integrated use of inorganic fertilizers with manures is a sustainable approach to improving the efficiency of fertilizers while also reducing nutrient losses [98]. Finally, it was concluded that, in recent years, integrated nutrient management systems are gaining importance for maintaining soil fertility, with the combined use of inorganic fertilizers and organic manures [93].

6.3. Municipal Waste Composts and Sewage Sludge (SS)

The production of sewage sludge (SS) has been dramatically increased in recent years due to the rise in the human population, the development of industry and agriculture and the increased demand for the adequate treatment of waste produced in large cities [99]. Composts produced by municipal wastes were sometimes used as organic fertilizers for crop nutrition. There are studies supporting that composted SS application increased soybean yields by 12% and 20%, respectively, compared to the control and conventional fertilization [100]; according to these authors, their findings confirm the benefits of composted SS application on infertile agricultural soils, representing a strong alternative source of micronutrients, compared to conventional fertilizers [100]. Apart from annual crops, composts produced from municipal wastes were also used as biofertilizers in fruit orchards; Baldi et al., (2010) [12] found that municipal waste composts increased root production (at a soil depth of 41–80 cm) in a nectarine (*Prunus persica* L.) orchard; in addition, the root lifespan was longer in compost-treated trees than in mineral-fertilized or unfertilized trees.

Since SS contains high levels of organic matter, N, P, Ca and several micronutrients [101], it may be used for fertilization purposes, instead of using expensive inorganic fertilizers in forest plantations [102]. Ferraz et al., (2016) studied soil fertility, growth and nutrition in *Eucalyptus grandis* plantations fertilized with sewage sludge and found that after its application, organic matter, N and P in the upper 5 cm of the soil were increased; in addition, N, P, Zn and Cu concentrations in *Eucalyptus* leaves were elevated. According to the same authors, fertilization with sewage sludge provided a rise of 50–90% in timber, compared to the control (unfertilized) plots [14]. Similarly, it was found that biometric values (height, base diameter, diameter at mid-height and number of leaves) for *Eucalyptus camaldulensis* plants were significantly higher when they were fertilized with sewage sludge (sludge/soil mixtures, where the sludge content was 20%, 40% and 60%), compared to the control (i.e., 100% soil) [58]. It was found that sewage sludge proved efficient in completely replacing P fertilization and micronutrients, and in partially replacing N fertilization, without decreasing maize productivity [103].

Based on the above data, it seems that organic fertilization with composts produced by municipal wastes and sewage sludge may be a promising strategy for tree crops; however, direct sewage sludge (SS) applications should mainly be preferred for forest plantations (because forest products do not directly enter the human food chain) [104], rather than for fruit tree crops, since serious concerns have been raised for consumers' health due to high heavy metal concentrations in the SS composition [105], and the subsequent high heavy metal accumulation in the edible parts (fruits) of tree crops. Finally, with regard to the influence of climatic conditions on heavy metal accumulation by SS application, it was found that under tropical climate conditions, due to rapid organic matter degradation, SS can provide toxic elements that may cause damage to the environment; thus, its application under these climatic conditions should be avoided [103].

6.4. Crushed Pruning Wastes and Other Composts

Different types of compost have been used until now as biofertilizers for crops. For example, the use of palm tree compost (P-compost) as an organic fertilizer for *Medicago sativa* L. was studied, with promising results in soil properties (organic matter, water retention capacity), nutrition (enhancement of P, K and N uptake) and agronomic traits of the plants (biomass production and grain yield). The authors concluded that this palm compost, at a moderate dose (30 tn ha^{-1}), could be highly beneficial for forage plant yields [106]. According to our opinion, similar palm composts may be used to satisfy either the nutritional requirements of *Phoenix dactylifera* L. or those of other fruit tree crops in the southern Mediterranean regions. Chocano et al., (2016) [15] used crushed pruning wastes (after a good incorporation into the soil) for organic plum cultivation purposes in southeastern Spain, with very promising results, while Baldi et al., (2021) [13] used a compost made from domestic wastes, mixed with pruning material from urban ornamental trees, for fertilization purposes of a commercial nectarine orchard; the application of compost either at a low (12.5 tn ha^{-1} yr^{-1}) or high rate (25 tn ha^{-1} yr^{-1}) did not increase the risk of pollution with toxic metals, while, at the same time, it increased the bioavailability of Fe, Mn and Zn [13]. Other composts that have been used for organic fertilization of tree crops consisted of sheep manure, mixed with wheat straw, in the proportion 60:40 [8]. Table 3 shows the nutrient content of some vegetal materials than can be used for compost production.

Table 3. Vegetal residues of some plant species that can be used for compost production (from Therios, 1996) [85].

Vegetal Material Used for Compost	N	P	K
		%	
Apple leaves	1.00	0.15	1.20
Leaves of *Medicago sativa* L.	2.45	0.50	2.10
Phaseolus vulgaris L. (whole plants)	0.50	0.10	0.50
Cabbage (leaves + stems)	0.37	0.10	0.45
Grass	0.50	0.10	0.25
Peach leaves	0.90	0.15	1.80
Pear leaves	0.70	0.12	1.20

Land application of organic materials has been a common practice in sustainable agriculture in recent years. The long-term recycling of plant residues, when combined with the application of compost in the soil, was found to substantially increase soil organic matter [107,108]. Kavvadias et al., (2018) [109] investigated the long-term application of carbon inputs (wood shredded, pruning residues, composted olive mill wastes) on soil properties in irrigated and rainfed olive orchards, from Messinia, SW Peloponnese, Greece; it was found that soil OM was significantly increased with time, particularly at the end of the experimental period, while total N was significantly reduced. The increase in OM after compost application to the soil was attributed to the relatively lower microbiological activity expressed by the basal respiration and therefore the low rate of C mineralization [110].

The difficulty in increasing soil C by crop residue inputs may be related to the decreased microbial carbon use efficiency [111]. Furthermore, other studies showed that soil C does not increase, as expected, in response to the application of crop residues [112,113]. Furthermore, in a similar study, the short-term effects of carbon inputs on soil properties, in relation to irrigation in olive orchards, were investigated [109]. It was concluded that the soil C content remarkably reduced by the addition of organic materials in irrigated soil parcels compared to the control (without the addition of organic materials), whereas SOC substantially increased by the carbon inputs in rainfed plots. In fact, favorable soil water conditions in irrigated fields compared to rainfed ones and nutrient enrichment of soil by carbon inputs enhance the mineralization of organic C [109]. In another study, woody chips (amendments) were used from tree branches of four tree species (poplar, elm, pagoda tree and grapevine); the conclusion was that these materials from locally available trees can serve as valuable amendments for desertified soils towards increasing rainfall capture, reducing the irrigation demand, improving soil health and promoting higher crop yields [114]. The correct use of crop residues helps in improving the soil structure, conserves soil moisture and leads to a reduction in dry weed mass, density and diversity.

6.5. Cover Crops (Leguminous, N-Fixing Plant Species)

Nitrogen (N) is the most important nutrient for crop growth and the major element supplied by fertilization; however, excessive use of N fertilizers increases the three main pathways of N loss (i.e., leaching, denitrification and volatilization), and the estimated N fertilization efficiency of crop production is less than 30% [115]. This results in high economic and environmental costs. In addition, excessive N fertilization reduces the soil microbes' population, especially fungi, and N_2-fixing bacteria [116,117]. Several strategies have been proposed to address problems associated with inefficient N use, but the most promising and comprehensive solution is the simultaneous adoption of mineral fertilizer techniques, such as splitting [118] and microdosing [119], the use of legume-based rotations, mixtures and perennial crops and the use of organic fertilizers and biological inoculants. The main purpose of cover crops is generally to provide a good ground cover to decrease rainfall runoff and soil erosion, as well as assisting in smothering weeds. However, the main problem with cover crops is the need to control them so that they do not compete strongly against the main crops or prevent main crop establishment through cover crop or residue mulch.

Cover crops have mainly been used in annual crop systems, planted during the fallow season, often only for 3–5 months, when the annual crops are not in production [120,121]; then, the cover crops are terminated and incorporated into the soil before planting the annual crop. Cover crops may be an alternative solution for fruit orchards in order to enhance soil fertility and microbiological activity, and to sustain yields. It is of high importance to use cover crops in tree cropping systems (using multispecies cover crop mixtures) and minimum tillage, or no-tillage, not only to enhance the soil microbiome but also C, N and P cycling, compared to mono-cropping, conventional tillage and inorganic fertilization [18]. The same authors support that evaluations of the interactions between the soil microbiome, cover crops, nutrient cycling and tree performance will allow for more effective and sustainable management of perennial cropping systems [18].

Different plant species may be used as cover crops (green manures) to boost soil fertility, improve soil biological properties and ameliorate crop nutrition; in this direction, it seems that *Trifolium pretense* L. would be one of the most promising species to achieve these goals in tree orchards. According to Tejada et al., (2008) [122], who studied the effects of different green manures (*Trifolium pretense* L.-TP, *Brassica napus* L.-BN and their mixture, i.e., TP+BN) on the soil biological properties, nutrition and yield of maize crops, all green manures had a positive influence on these parameters; however, soil microbial biomass and enzyme activities increased more in the TP-amended soil, followed by the TP+BN and BN treatments.

Cover crop species may be established either in the middle of inter-rows or between trees in fruit orchards, offering significant advantages in enriching the soil with N, since most of these species (legumes) are expected to provide N to the soil through the process of N fixation, during which atmospheric N (N_2) is converted to NH_4 in the root nodules of leguminous plants [18,123]. The use of no-tillage and cover crops between rows in perennial crops (olives, nuts and grapes) is steadily increasing in many Mediterranean areas. Michalopoulos et al., (2020) [124] proposed a set of alternative agricultural practices in olive groves located in southwest Peloponnese and in Crete (Greece). Among them, there were a no-tillage/reduced tillage system and a cover crop technique. The traditional practice (seasonal (winter) 40% soil coverage by spontaneous vegetation) was replaced by the enrichment of the natural soil vegetation of the olive groves by a seed combination consisting of 100 kg ha^{-1} leguminous crops and 10 kg ha^{-1} of seeds of *Avena sativa*, in November or December. Grove vegetation was mowed during spring without incorporating into the soil. After a 5-year experimentation period, an increase in the soil covering up to 100%, as well as an increase in the biodiversity of the flora on the floor of the olive groves was found. Based on the above results, the authors suggested that cover crops' lifetime could be prolonged in Peloponnese up to April in years with sufficient spring rainfall. In contrast, in Crete, cover crops should be terminated by the end of March, at the latest, to avoid water competition with olive trees [124].

There are various crop alternatives to be used as vegetative cover, such as grains, legumes, root crops and oil crops. All of them are of great benefit to the soil. The use of legumes grown in rotations or intercropping is characterized as a sustainable practice of introducing N, particularly in low-input agroecosystems [125]. In particular, legumes can deposit significant amounts of N in the soil during growth [126,127]. Legumes introduce N into the soil via biological N_2 fixation and N rhizodeposition and transfer N in companion plants [128,129]. In addition, they can fix N due to symbiosis with rhizobia, and the fixed N can be transferred to intercropped non-legumes in mixed cropping systems, or it can follow crops in rotations. Indeed, the turnover of N in the belowground parts is the main source of transferable N between plants [129,130].

It has been estimated that 40 to 75% of the total N which is contained in a legume cover crop is available in the soil for subsequent crops [131]. In a 97-day lab incubation experiment, it was found that white clover-amended soils presented more than five times higher net mineralization (54%) than the soils amended with composts (vegetable, fruit and poplar tree composts) or cattle manure (4–9%) [53]. According to the same authors, N was mineralized faster in the clover-amended soils than in the soils amended with manure or composts. Since the N mineralization potential differs among organic amendments, the application time and type of organic amendment should be matched to crop nutritional needs [53]. In addition, according to our opinion and based on the data of Masunga et al., (2016) [53], cover crops may better satisfy the N nutritional needs of crops (via additional N fixation/input from the atmosphere, and higher net and speed mineralization) compared to other organic materials used as soil amendments; this is of high agronomic importance for tree growers in order to reduce N fertilization inputs, which is one of the main targets of sustainable agriculture. The amount of N provided by leguminous plants depends on the species used as cover, the total biomass produced, the N concentration in plant tissues, the ability of species to fix N from the atmosphere and the environmental conditions affecting the growth of the selected legume [132].

In addition to the potential use of cover crops in the frame of sustainable agriculture (to sustain soil fertility and decrease N fertilization inputs), some legume species may also be used in organically fertilized, marginal, eroded agricultural sites, in order to enhance the low organic matter levels and N availability. Legumes (as cover crops) may be established in mountainous olive orchards with little organic matter. It was found that the implementation of a legume cover crop in these organic olive orchards would reduce erosive processes and increase the amount of N in the soil. From the obtained results, it was indicated that *Vicia ervilia* was the legume that presented the best behavior in the increase in the N content in the soil [133]. Legumes also have a substantial role to play in enhancing soil carbon sequestration. Several legume crops are being used as green manure. They improve the nutrient cycling, soil organic matter content and nutrient-supplying capacity of soils. It is well known that the inclusion of legumes into crop rotations increases soil organic matter compared to rotations without legumes [134]. It was estimated that, with the inclusion of leguminous crops, shrubs and tree species in conventional systems, the annual C sequestration rate could be increased by 20–75 g C m^{-2} [135].

The positive impact of legumes on SOM is attributed to the high C input through the high amounts of crop residues remaining in the soil, biological N fixation and the low disturbance of the soil under the crop [136]. These biological N-fixing systems can reduce the internal inputs of industrial N fertilizers [137]. Moreover, legumes play a significant role in sustaining soil health because it has been shown that legumes can solubilize insoluble P in the soil, improve the soil physical properties and increase soil microbial activity [138,139]. The carbon sequestration potential and the amount of organic C returned by leguminous species to the soil are mainly dependent on specific legume species, growth parameters, plant physiology, soil and climatic conditions, prevailing cropping systems and agronomic interventions during the crop growth period [140].

7. Conclusions and Future Perspectives

In conclusion, organic fertilization offers many benefits to agroecosystems, such as the improvement in soil physical properties and fertility, the enhancement of soil microbiology and the promotion of soil health. In contrast, within the main drawbacks of organic fertilizers, their inability to promptly satisfy the N nutritional needs of crops, due to the slow mineralization rate of N, should be highlighted; this may be solved, in many cases, with the supply of organic N, complementary to inorganic fertilization (mixed fertilization), which seems to be, in many cases, a more realistic approach. With regard to the influence of organic fertilization on tree crop productivity, according to many researchers, a similar biomass, yield and productivity of tree orchards were observed between inorganic and organic fertilization. Furthermore, new interesting aspects and impacts of innovative organic fertilizers' application on fruit quality were recently revealed and were mainly attributed to the enhancement of the abundance of potentially beneficial soil microorganisms. Among the most commonly used biofertilizers for tree crops are manures, OMW and other by-products of agricultural production, sewage sludge, composts, crushed pruning wastes and cover crops; according to many published data, the results were, in most cases, more than promising. It is estimated that, within the coming years, innovative organic fertilizers (enriched with beneficial microorganisms) will play a crucial role in sustaining, or even enhancing, orchards' yields. In addition, they will also meet society's demand for more healthy and qualitative fruit production towards, in parallel, protecting the environment (via decreased inorganic fertilization rates) and improving the ecosystem services of tree orchards.

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