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Review

Fertilization and Soil Microbial Community: A Review

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Abstract: The present paper reviews the most recent advances regarding the effects of chemical and organic fertilizers on soil microbial communities. Based on the results from the articles considered, some details are presented on how the use of various types of fertilizers affects the composition and activity of soil microbial communities. Soil microbes have different responses to fertilization based on differences in the total carbon (C), nitrogen (N) and phosphorus (P) contents in the soil, along with soil moisture and the presence of plant species. These articles show that the use of chemical fertilizers changes the abundance of microbial populations and stimulates their growth thanks to the nutrient supply added. Overall, however, the data revealed that chemical fertilizers have no significant influence on the richness and diversity of the bacteria and fungi. Instead, the abundance of individual bacterial or fungal species was sensitive to fertilization and was mainly attributed to the changes in the soil chemical properties induced by chemical or organic fertilization. Among the negative effects of chemical fertilization, the decrease in enzymatic activity has been highlighted by several papers, especially in soils that have received the largest amounts of fertilizers together with losses in organic matter.

Keywords: microorganisms; microbial activity; fungi; farming practices; soil fertility and productivity

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1. Introduction

Crop production is currently expanding globally due to an increased demand for food, animal feed and biofuels; the latter has been stimulated by the increase in oil prices making bioenergy crops more competitive and profitable compared to fossil fuels [1]. Currently, 47.9 million km^2 are devoted to agriculture, which is about 50% of habitable land [2].

Higher yields and better harvest quality can be achieved through the optimized use of fertilizers and the implementation of strategic production practices. Chemical fertilizers (also termed mineral, inorganic or synthetic fertilizers) contain a high concentration of a primary nutrient (nitrogen, N; potassium, K; phosphorous, P) as inorganic salts. Secondary elements (calcium, magnesium and sulfur) can also be added to soil by chemical fertilizers. Micronutrients (boron, manganese, iron, zinc, copper, molybdenum, cobalt and chlorine) [3] are in general absent in NPK chemical fertilizers and can be supplied by specific synthetic and expensive plant nutrients with soil or foliar applications [4].

The nutrient content in chemical fertilizers is indicated as the N:P:K rate, representing the percentages of nitrogen, total phosphorus (in the form of phosphorus pentoxide, P_2O_5) or total K (in the form of potassium oxide, K_2O). If they also contain secondary elements, numbers in brackets specify calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na_2O) or sulfur trioxide (SO_3) content.

The majority of the inorganic fertilizers (with the exception of N) is extracted from rocks using physical or chemical processes. N fertilizers (mainly as ammonium—NH_4^+—

and nitrate—NO_3^-: urea, urea ammonium nitrate, ammonium nitrate and calcium ammonium nitrate) are produced by combining atmospheric N_2 with hydrogen (mainly from hydrocarbons such as natural gas—CH_4) to obtain anhydrous ammonia (NH_3), which can be used directly as a plant nutrient or converted into other different N fertilizers [5,6]. Phosphate fertilizers (principally single superphosphate, triple superphosphate, monoammonium phosphate, di-ammonium phosphate and ammonium polyphosphate liquid) are extracted from natural phosphate rock deposits [7]. K fertilizers (potash muriate, KCl; potassium sulfate, K_2SO_4; potassium nitrate, KNO_3; sulfate potash magnesia, $K_2SO_4 \cdot MgSO_4$; kainite, KCl + NaCl + $MgSO_4$) are produced by different chemical processes [8].

Differently, organic fertilizers (Table 1) are derived from plant- or animal-based materials or other organic constituents that are either a by- or end-product of naturally occurring processes, containing both the essential nutrients and micronutrients for plant growth. They also comprise biofertilizers (bacteria, algae, fungi or biological compounds), including plant-growth promoting bacteria [9–11].

Inorganic and organic fertilizers have an important role in increasing agricultural production, but the use of mineral fertilizers is constantly growing, with an estimated total 186.67 million tons in 2016 [12]. There is increasing concern regarding the negative environmental effects of chemical fertilizers. In fact, they can cause serious greenhouse gas (GHG) emissions and pollution of soil and water ecosystems. For example, synthetic nitrogen fertilizers have been recognized to be the most important factor contributing to direct N_2O emissions into the atmosphere as a consequence of their biodegradation by soil microorganisms [13]. In addition, only 50–60% of synthetic nitrogen fertilizers added to soil is usually taken up by crops [8], and the rest runs off into water bodies (surface or groundwater [14]) due to their high dissolution properties. A possible alternative is the use of controlled-release fertilizers (coated and uncoated fertilizers with a low solubility) [15], but they are expensive and, therefore, used mainly for high-value crops (e.g., vegetables, fruits, flowers, ornamentals) [8]. Inhibitors of nitrification and urease processes can also be used for maintaining N in its soil-stable form by slowing its conversion to nitrate or delaying the first step of degradation of urea [16]. For these compounds (such as dicyandiamide, thiosulfates, 3,4-dimethylpyrazole phosphate), there is a lack of correlation between laboratory testing data and the actual field data [17]; there is also some concern about the potential for some of them to enter the food chain [18].

Phosphorus availability to plants after chemical fertilization can vary depending on the type of fertilizer used and, even under the best conditions, only about 25% of applied P is taken up by plants during the first cropping season [19]. Depending on the pH and moisture of soil, P can than precipitate (at high pH due to the presence of calcium and magnesium and at low pH due to an iron and aluminum presence) [20] or can be immobilized in soil [21]. The use of P fertilizers also leads to eutrophication (when P runs off to surface waters) [22]. Potassium has several beneficial roles in plant physiological and metabolic processes, including resistance to biotic and abiotic stresses and absorption and utilization of N and P by crops [23]. On the other hand, fertilization with KCl does not increase crop yields and has detrimental effects on the quality of major food, feed and fiber crops, with serious repercussions for soil ecosystem and human health [24].

Conversely, organic farming using organic fertilizers that are environmentally friendly amendments (e.g., microbial fertilizers [25,26], manure, compost) can be a good alternative and can reduce the consequences of environmental pollution from synthetic fertilization. In fact, organic fertilizers for example gradually release primary and micronutrients into the soil, maintaining a nutrient balance for a healthy growth of crop plants. They can also be an effective source of soil microbes, while also improving soil structure [27]. Table 1 shows a list of the main organic fertilizers.

Table 1. Organic fertilizers.

Type	Production Process and Materials	Pros and Cons	Refs.
Biochar and biochar-based fertilizers	Pyrolysis (thermal decomposition of organic matter with absence of or very limited access to oxygen), hydrothermal liquefaction and gasification of different type of biomass (agricultural residues, sewage sediment, forest waste, energy crops and residues from agro-food processing)	They improve physical, chemical and biological properties of soil, together with nutrient absorption and cation exchange capacity. They reduce the uptake of metals, pesticides, PAHs, engineered nanomaterials, and pharmaceuticals by plants. The type of biomass used influences the biochar properties. If used together with other fertilizers, they can reduce their beneficial effects.	[28–30]
Biofertilizers or microbial fertilizers (bacteria, algae, fungi or biological compounds), including-plant-growth-promoting bacteria	Isolation of microbes, screening, scale-up	Increase soil fertility by various macro- and micronutrients; improve soil biodiversity and plant growth by increasing the accessibility to or uptake of nutrients from a limited soil nutrient pool. Power of biofertilizers depends on the type of microorganism used and their metabolic activity during and after field applications.	[9–11,31,32]
Biosolids	Stabilization of organic solids from sewage treatment processes (mainly from biological treatment of wastewater). The stabilization reduces the pathogen presence	They contain macro and micronutrients in variable quantities; K concentrations are commonly low, so that an additional K fertilization may be necessary. They can contain pathogens, traces of metals, pharmaceuticals, personal care products and other organic contaminants (e.g., phthalates, pesticides, phenols, PCBs, dioxins).	[33,34]
Bio-surfactants	Surface-active biomolecules produced by microorganisms (bacteria, yeasts and fungi); they have both hydrophilic and hydrophobic regions	They increase the surface area of hydrophobic substrates (e.g., hydrocarbon pollutants, heavy metals or nutrients) increasing their bioavailability (solubilisation/desorption). They also regulate the attachment and removal of microorganisms from surfaces. Used for hydrocarbon biodegradation in contaminated soil, for plant pathogen elimination thanks to their antifungal, antiviral, insecticidal and antimycoplasma activities and for increasing the nutrient bioavailability for beneficial plant-associated microbes.	[35–37]
Compost	Composting (biological decomposition under controlled moisture, self-heating and aerobic conditions) of animal manure, sewage sludge, municipal solid waste and green wastes	Simplicity of technologies and possibility of implementation on every farm; quality protocols are provided in several countries for reducing pathogen, heavy metal and organic pollutant presence.	[38,39]
Green waste or biowaste	Different origins: crop residues, food and kitchen waste. It does not include forestry or agricultural residues, manure, sewage sludge or other biodegradable waste such as natural textiles, paper or processed wood.	Improve soil structure; low nutrient content; could contain plant pathogens.	[40]

Table 1. *Cont.*

Type	Production Process and Materials	Pros and Cons	Refs.
Digestate	Anaerobic fermentation of different organic wastes (food waste, manure and energy crops). Microorganisms, under anaerobic conditions, convert organic matter into biogas and digestate	Production of biogas; digestate could contains residual concentrations of contaminants (e.g., plastics, pharmaceuticals, including antibiotics, etc.) depending on the type of biowaste used; a duff layer could be formed on soil surface that hinders seed germination.	[38,41–43]
Manure	Mainly from beef, pig or poultry livestock	Improve soil structure (depending on its origin). Increase in potentially mineralizable N. Potentially pathogenic; could contain heavy metals used for animal feed, manily Zn and Cu; could contain pharmaceutical residues and antibiotic resistance genes; water pollution by nitrates or by P in intensive livestock productions by spreading manure rich in N and P out of the soil capacity.	[44–47]
Vermicompost	Vermicomposting, a bio-oxidative process involving several organic materials (e.g., sewage sludge, crop residues, manure, digestate) using mainly epigeic earthworm species and different microorganisms.	It is rich in microorganisms, nutrients, vitamins, and growth hormones; used also as biocontrol agents against diseases and pests. The nutrient-rich compost could also be used for biogas production.	[48–51]

Fertilizers and amending materials are regulated in the EU by the Regulation 2019/1009. In the US, they are differently regulated at the state level rather than by the federal government.

Fertilizers in China are controlled by several regulations and standards. Importing, producing, selling or utilizing un-registered fertilizers is not allowed. Moreover, fertilizers sold in China also have to meet important product standards and requirements for their marking, with the compulsory national standard GB 18382-2021, which was issued in 2021 and comes into force on 1 May 2022. The "Mandatory national standard GB 38400-2019 Limit requirements for toxic and harmful substances in fertilizers" that comes into force on 1 July 2020, defines the hazardous substance limits in fertilizers (i.e., heavy metals).

In Brazil, the main regulatory agencies for fertilizers are MAPA (the Brazilian Ministry of Agriculture, Livestock and Food Supply), ANVISA (Brazilian Health Regulatory Agency), MMA (Brazilian Ministry of Environment) and INMETRO (Brazilian National Institute of Metrology, Quality and Technology). Law 6894/80, also called the "Fertilizer Act", contains the general rules regarding the registration and classification of such products. It is devoted to the inspection of the production and trade of fertilizers (including also correctives, inoculants, stimulants, bio-fertilizers, remineralizers and substrates for plants). All these fertilizers have to be registered at the Ministry of Agriculture. The Fertilizer Act is regulated by the Decrees n. 4954/2004 and n. 8384/2014.

In India, the Ministry of Chemicals and Fertilizers (https://fert.nic.in (accessed on 18 January 2022)) is devoted to the regulation of fertilizers. The Fertilizer Control Order provides for registration of fertilizer manufacturers, importers and dealers; it is specifically for all fertilizers manufactured/imported and sold in the country, regulating also fertilizer mixtures, and the packing and brand description on the fertilizer bags etc. Chemical fertilizer consumption has been generally increasing in India during the last 4 years, with a maximum of 59.88 million tons of fertilizer products used (mainly urea, di-ammonium phosphate, murate of potash, complexes and single super phosphate), as recently reported by the Indian Ministry of Agriculture and Farmers' Welfare (https://pib.gov.in/PressReleseDetail.aspx?PRID=1696465 (accessed on 18 January 2022)).

Soil biota encompasses a huge diversity of organisms, including microorganisms (i.e., bacteria, fungi and archaea), which are the largest group of soil organisms in terms of number and biomass [52]. Soil microbial communities play important roles in ecosystem functions and regulate key processes, such as the carbon and nitrogen cycles [53]; for example, microorganisms carry out the ecological functioning of N_2-fixation, ammonia-oxidation, denitrification and ammonification. Microbial communities are also key players in the degradation of various compounds, including organic pollutants such as pesticides [54], and they promote plant growth and disease control [55]. The diversity and biomass of soil microbial communities are the major regulators of fundamental ecosystem processes [55], supporting crop production [52]. In fact, a good soil quality, which means a diverse and abundant microbial community and activity, is a pre-requisite for plant growth and, consequently, for crop production [56]. In particular, soil microbial biomass, activity and diversity are an indicator of soil fertility and ecosystem productivity [57,58]. For this reason, they are used as indicators of soil quality and health [52,59]. Soil quality is defined as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintaining or enhancing water and air quality, and supporting human health and habitation [60]. Microbial populations vary depending on different abiotic factors such as soil type, presence/absence of plants and climate; their responses to similar fertilization treatments can thus be different depending on the above-mentioned abiotic factors. During the long-term process of evolution, soil, plants and microbes co-evolved to form relatively stable relationships within a given ecosystem. In fact, the soil microbial community has recently been termed the soil microbiome [53,61,62]. Changes in soil microbial communities induced by environmental changes could influence the relationships between microorganisms and plants and may negatively influence soil fertility and crop productivity. Consequently, studying the effects of chemical/organic fertilizers on the natural microbial community is of crucial importance. For example, understanding how NPK chemical fertilizers influence the microbial biomass, which is an indicator of soil fertility and quality, is a basic prerequisite for understanding microbiological processes [63], in order to preserve the ecosystem functions of soil.

These research themes are an important part of soil ecology, as pointed out by several international authorities (e.g., EU commission, FAO [64,65]). The use of inappropriate farming practices (e.g., excessive use of chemical fertilizers and pesticides) and frequent changes in land use may cause variability in soil microbial communities, which can have significant effects on soil fertility and productivity [66].

The present article reviews the importance of soil microbes for the soil ecosystem, with a particular emphasis on the influence of chemical and organic fertilizers on the soil microbial community. In particular, microbial biomass, activity and diversity were taken into account as parameters. For microbial activity, dehydrogenase activity, a general indicator of microbiological activity [67,68] is considered.

2. Materials and Methods

This review considers articles published between 1990 and 2022 regarding the effects on soil microorganisms of chemical fertilization in long-term field experiments, in particular with reference to control soils (not fertilized) or soil fertilized with organic amendments. The articles were both original studies and literature reviews, scoping reviews and systematic reviews with state-of-the-art knowledge of the topic [69].

The criteria used in this review for searching articles were:

- Type of publications (only original studies or reviews were considered);
- The main direction of the systematic review consisted in reviewing the fertilizer types and fertilizer treatments used in different countries of the world;
- Effects of chemical fertilizer management on soil microorganisms in agroecosystems across the world, also compared with organic fertilization;

- Influence of intensive and/or long fertilization on the numbers and activities of microbial communities in soils;
- Comparison between the various fertilizer regimes and their effects on soil microorganisms.

Exclusion criteria consisted in:

- Editorials;
- Studies published in a language other than English;
- Studies in specific extreme areas (e.g., arctic or arid soils).

To find the main relevant studies, ERIC (Education Resources Information Center) was used together with numerous databases, including Web of Science, Science Direct, SpringerLink and Google Scholar. The primary keywords used in the different databases were: "use of chemical fertilizers", "influence of phosphorus on soil bacteria", "fertilizers and soil microorganisms", "soil bacteria affected by fertilizers", "long-term fertilization effects on soil microorganisms", "ecological consequences of the fertilizers" and "combined fertilization".

In Figure 1 a sketch containing the methodology steps used is presented.

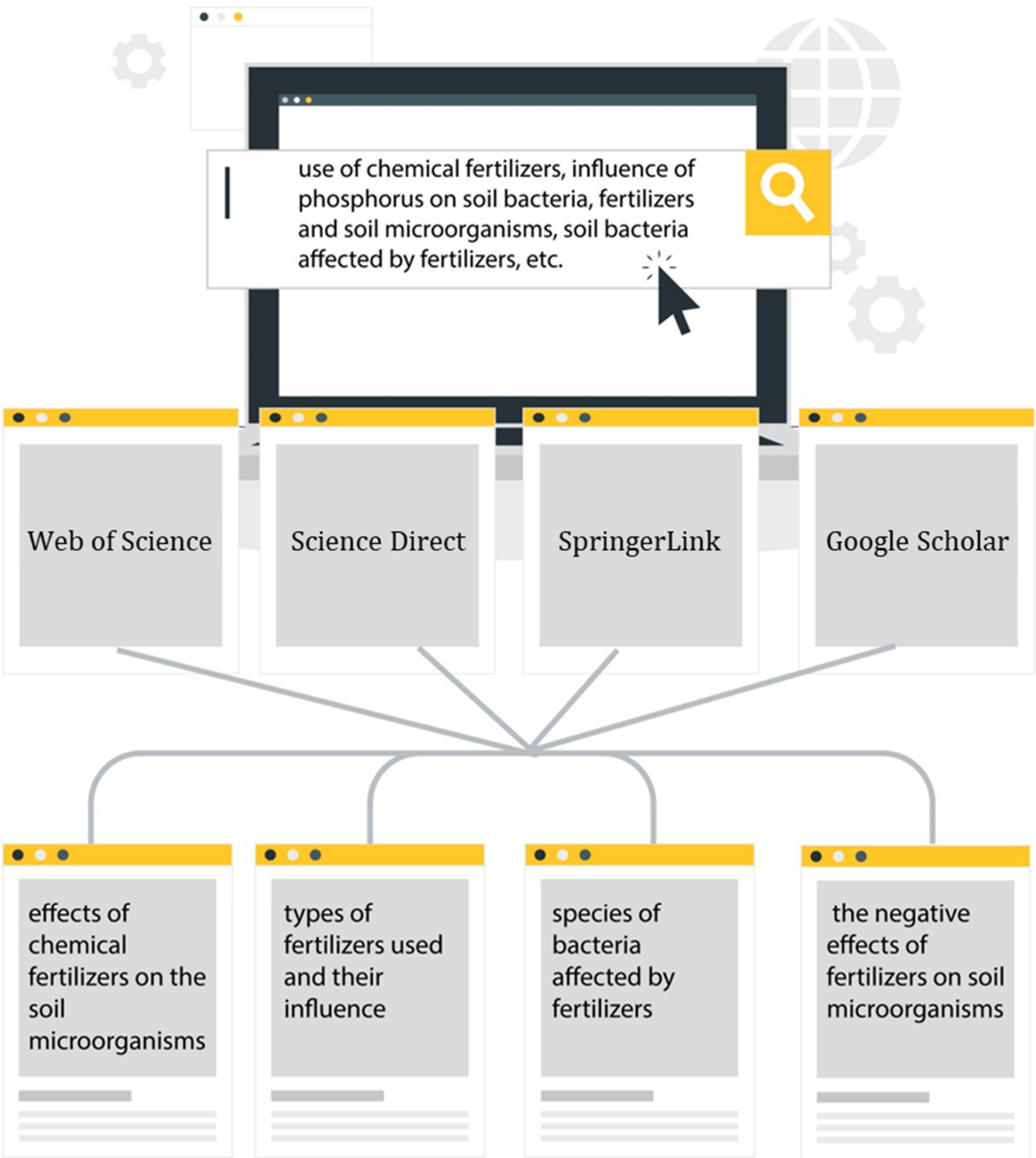

Figure 1. Methodology steps.

3. Results and Discussion

Overall, a total of 52 articles were considered (Table 2). A significant proportion of the papers on the effects of inorganic or organic fertilizers on soil microbial communities were published by Asian authors (Chinese), representing about 28% of the total. Other important studies have been performed by European and North American authors, with numerous works being dedicated to this subject during recent years. Because the effects of fertilizers were not influenced by Country, the main considerations in the following paragraphs were grouped in categories such as effects of chemical fertilizers (NPK) on soil microorganisms/soil microbiome, types of fertilizers used and their influence, species of bacteria affected by fertilizers and the negative effects of fertilizers on soil microorganisms (Table 2).

Table 2. Relevant data from the articles distributed on countries (continents) and research topics.

Subject	Articles Distribution by Countries (Continents)			
General	**Europe**	**China**	**North America**	**Others**
Effects of chemical fertilizers on biomass, activity and diversity of soil microorganisms	1	7	2	2
Types of fertilizers used and their influence on soil microbial community	8	3	1	4
Bacterial and fungal species affected by chemical or organic fertilizers	3	6	1	3
Negative effects of chemical fertilizers on soil ecosystem	5	1	2	5
Total	18	17	4	13

3.1. Effects of Chemical Fertilizers on Biomass, Activity and Diversity of Soil Microorganisms

It has been generally shown that both chemical and organic fertilizers can directly stimulate the growth of specific microbial populations by supplying nutrients [70], leading to an increase in total microbial numbers [71–74], improving microbial activity [75] and determining a switch in microbial diversity. A high soil microbial diversity is crucial for the productivity and stability of the agroecosystems [76]. In several studies, mineral fertilization has been found to reduce microbial diversity, including the plant-beneficial microbial taxa [76]. Meta-analysis of microbial communities, based on 107 datasets from 64 long-term trials from around the world, concluded that mineral fertilizer application (in particular N fertilizer treatment) leads to a 15.1% increase in microbial biomass compared to unfertilized control plots; moreover, N application (urea and ammonia fertilizers) can have a temporary or stable effect in increasing pH [77–79]. However, the use of a chemical fertilizer alone does not lead to a remarkable increase in soil microbial abundance. This was observed in a rice–wheat cropping system [80], in a drip-irrigated cotton systems [74] and in paddy field soils [81]. Long-term mineral fertilization, and in particular N addition, increases microbial biomass beca.use soil microorganisms may be carbon- or N-limited. The increase is significant if soil pH is >5; in other cases, fertilization reduce microbial biomass [77].

Soil-available P and total N are the most important factors influencing the abundance of microbial communities involved in the nitrogen cycle [82]. However, chemical fertilization, in particular N addition, was found to decrease bacterial alpha-diversity [83], although a recent study found that soil fertility and plant yield was mainly due to bacterial and archaeal abundance and community structure rather than bacterial, archaeal or fungal alpha-diversities [84]. In fact, the increase in microbial biomass has been attributed to better plant growth, which results in higher rhizodeposition [85]. The latter was found to be more active in determining a shift in the fungal community [86]. That is, soil bacteria were more sensitive than fungi to fertilization practices [87,88]. In addition, the plant composition and carbon substrate utilization patterns of rhizobacterial communities were more diversified in unfertilized plots than in chemical fertilized plots in grasslands [89]. Long-term NPK applications have been found to result in a loss in soil organic matter (SOM), especially in arid and semi-arid areas or where a monoculture is performed (e.g., corn) [90–92]. An increase in SOM by mineral fertilizers has been found only when they are applied in combination with organic amendments [93,94]. SOM quality greatly influences soil microbial community composition [95]. Soil quality and crop yield also depend on SOM content [4]. The latter affects the availability of micronutrients, with higher micronutrient amounts in higher SOM content [4]. Moreover, SOM quality (e.g., organic acid, protein, humic acid and lignin content) and its biodegradability essentially influence microbial characteristics (e.g., specific population size, microbial activity and composition) [94,96]. Consequently, any SOM depletion has negative consequences for microbial community richness together with lower plant health, growth and productivity.

In general, organic fertilizers improve soil structure (in terms of particle-size fraction [97]), and they are responsible for a more balanced and stable nutrient supply, which can sustain a more diverse microbial community if compared to mineral fertilizers [98]. Moreover, organic fertilization is reported to increase microbial activity and SOM content and improve the chemical and physical properties of soil better than inorganic fertilization [99–101], preventing the decrease in soil pH due to mineral fertilizer application [90]. In any case, long-term inorganic or organic fertilization significantly decreased soil pH if compared to a non-fertilized control [86], although soil pH changes due to organic amendments depend on the amendment used [102]. For example, some biochar was found to increase soil pH [102], whereas manure could in general decrease soil pH [103].

Dehydrogenases are respiratory enzymes that oxidase organic compounds allocating two hydrogen atoms from these compounds to electron acceptors, producing energy [58]. These enzymes are present in all soil microorganisms and are not present as a free form, representing only the activity of live microbial cells. Consequently, dehydrogenase activity has been considered as an indicator of soil microbiological activity [58,67,68,104].

Dehydrogenase activity (DHA) was found to be lower in soils that had received high (160 N, 120 P_2O_5, 160 K_2O) amounts of NPK fertilization [98], suggesting that these enzymes are highly sensitive to the inhibitory effects associated with high mineral fertilization. In addition, long-term P-deficiency fertilization can significantly decrease DHA together with soil microbial biomass and bacterial diversity [90]. Although an NPK balanced fertilization can increase DHA, the higher increase is always found with organic fertilization [71]. Applying phosphorus-based fertilizers has been shown to lead to seasonal variations in microbial activity, as well as in the abundance of specific bacterial and fungal phospholipid fatty acid (PLFA) indicators of soil microbial biomass [105–107].

In their experimental study, Enebe and Babalola [108] examined the response of maize bacterial, fungi and archaeal communities to compost and inorganic fertilizations. The results showed that both fertilizers influenced the maize rhizosphere microbial community but the organic amendments provided the most stable microbial community; these results were also found by Zhang et al. [109], in which higher levels of NPK treatments (60 kg of NPK fertilizer as N/ha) negatively affected the microbial community structure and abundance in an agricultural soil.

On the other hand, long-term fertilization with organic amendments can both mitigate the negative effects and exploit the positive effects of climate change on crop production, enhancing soil quality and improving crop productivity, as was observed by several authors (e.g., Song et al. [110] in northeast China).

In an overall view, although it is not possible to summarize all the beneficial effects of organic fertilizers because they are very different in type of production, content in essential nutrients (NPK), pH, structure, etc., they always improve soil structure and organic matter content of soil, together with an increase in microbial communities. Moreover, thanks to the soil quality improvement, they also favor microbial community abundance and activity. On the other hand, although mineral fertilizers, apart from their environmental side effects (GHG emission, soil and water pollution), provide essential nutrients, long-term application contributes to soil depletion. In fact, soil treated only with chemical fertilizers relies solely on the root residues and exudates of the crops to increase carbon input [93].

3.2. Types of Fertilizers Used and Their Influence on Soil Microbial Community

The sustainable development of agroecosystems is based on a better understanding of the complex responses of microbial communities to the various organic and inorganic fertilization regimes, as highlighted by Pan et al. [111], demonstrating that a better understanding of the complex responses of microbial communities to various organic and inorganic fertilizations is critical for a sustainable development of agroecosystems. They found that using chemical fertilizer together with manure clearly increased soil fertility and were recommended for further optimization of fertilization patterns. In addition, the results of their research suggested that organic and inorganic fertilizers dominated in shaping bacterial and fungal community distributions in fluvo-aquic soils.

Nakhro and Dkhar [81] compared the use of organic fertilizers with inorganic ones, observing that organically treated soils had the largest number of microorganisms (fungi and bacteria) and microbial biomass carbon. Chemical fertilizers, on the other hand, have been shown to have a smaller effect than other soil treatments on bacterial composition and diversity [112].

Comparing the effects of chemical fertilizers with manures (farmyard manure, slurry and green manure), Edmeades [113] concluded that there is no significant difference in the long-term effects on crop production between these two types of fertilization. However, manured soils had higher organic matter contents and higher numbers of microfauna than soils added with chemical fertilizers. The manured soils were also more enriched in P, K, Ca and Mg in the topsoil and nitrate, N, Ca and Mg in the subsoil.

When an organic fertilizer is applied to soil, its decomposition is due to bacteria and fungi, which in turn support the soil fauna chain. The ratio of fungal to bacterial biomass can be considered an indicator of the activity of two pathways of the soil food web, formed by fungivores or bacterivores and their predators, respectively [114]. In general, bacteria are prevalent under conventional tillage, whereas fungi dominate under no-tillage. The use of nitrogen fertilizers by applying organic amendments decreases the fungi/bacteria ratio and can decrease the soil pH [114]. For this reason, several countries encourage farmers in economically developed areas to reduce their N fertilization rate [115]. Cruz et al. [116] concluded that mineral fertilization, which modifies available N and P and hence changes in soil fertility, can be a selective force causing structural and functional shifts in the soil microbial community. Furthermore, a mixed application of N, P and K has been shown to increase soil microbial biomass and diversify bacterial communities [117]. In several studies nitrogen addition is a key factor in bacterial and fungal community composition shifts [87].

3.3. Bacterial and Fungal Species Affected by Chemical or Organic Fertilizers

Several authors have demonstrated that the structure of the soil microbial community (composition, diversity, and relative abundance of specific taxa) changes after chemical or organic fertilization [25,80,118–120]. In fact, the latter affects microbial growth and competitiveness because different bacterial and microfungal groups can vary in their ability to use the different nutrient forms found in soil [76,90,121]. For example, *Knufia petricola* and *Zygomycetes* fungi were found only in the inorganic fertilization of soil. *K. perticola* is a microcolonial Ascomycete adapted to extreme environments, and *Zygomycetes* are typical *r*-strategists with a rapid growth with simple carbon sources [122]. Moreover, some typical bacteria from organic amendments (e.g., *Firmicutes* and *Myxococcales*) were found as primary constituents in manured-traded soils [121,123]. Specific microbial groups (*Firmicutes*, *Proteobacteria*, and *Zygomycota*) are stimulated to grow in organic fertilizer treatments, because they prefer nutrient-rich environments, and are capable of degrading complex organic compounds [76].

Many studies have focused on the impact of different types and regimes of fertilization on the soil microbial communities, and the results are in some case conflicting for chemical fertilizers. For example, Sun et al. [82] focused on the effects of long-term fertilization with NPK or NPK + organic amendments on specific bacterial and archaeal genes involved in the nitrogen cycle. They suggested that the genes for ammonia-oxidization are more sensitive than nitrogen fixers and denitrifiers to fertilization. Although they found that NPK increased soil fertility in terms of genes involved in the nitrogen cycle, the organic amendments induced greater gene abundance. Interestingly, soil available P was the most important factor influencing the abundance of functional communities involved in the nitrogen cycle.

Long-term agricultural organic and chemical fertilization significantly affects nitrogen cycling in soils [97,98,124–126]. For example, in calcareous soils, N fertilization increases the potential nitrification rate but reduces the efficiency use of N and changes the beta-diversity of ammonia-oxidizing bacteria (AOB), reducing the relative abundance of *Nitrosospira* (nitrite-oxidizing bacteria) and increasing the relative abundance of *Nitrosomonas* (which oxidize ammonia to nitrite) [126]. On the other hand, mineral and organic fertilizer application significantly increased the species richness and alpha-diversity of AOB [125]. In contrast, Wang et al. [78] revealed that the long-term application of manure and chemical fertilizers significantly affected microbial community structure, and specifically, NPK significantly reduced the alpha-diversity of the soil microbial community.

The influence of fertilization on the *r* to *K* member ratio has been reported in some papers. In general, *r*-strategists grow fast when the substrate is abundant, and include copiotrophic bacterial taxa such as *Proteobacteria* and in particular *Alpha*- and *Beta-Proteobacteria*, *Firmicutes*, *Actinobacteria* and *Candidatus Saccharibacteria*. *K*-strategists can grow when resources are limited and include oligotrophic bacteria such as *Acidobacteria*, *Gamma*- and *Delta-Proteobacteria*, *Gemmatimonadetes, Verrucomicrobia* and *Chloroflexi* [76,127,128].

The application of chemical fertilizers has been reported to enrich the *K*-strategist bacterial community [76,93,129,130]. It was for example found in a silt loam soil in a long-term experiment with wheat (*Triticum aestivum* L.) plantation. Wang et al. [131] in meadow grassland soils reported that N and P fertilizations shifted soil microbes towards an *r*-selected community. Nutrient addition (both organic and chemical) have been found to enrich copiotrophic taxa affiliated with the *Pseudomonadaceae* and *Cytophagaceae* bacterial families but to reduce some *Acidobacteria* [86]. In particular, *Cyanobacteria* (an active N-fixing group) increased in soils amended with inorganic fertilizers. Manure application, on the other hand, increased the relative abundance of the *Gamma-Proteobacteria* group (responsible for organic substrate decomposition) and *Nitrosomonadaceae* (*Beta-Proteobacteria*), which play a vital role in converting ammonium into nitrate [86].

Overall, organic and inorganic fertilizers generally have positive effects on numerous soil bacteria, the most representative of which is *Azotobacter*. The latter is in fact a free-living, nitrogen fixing aerobic soil bacterium able to make available to plants a considerable part of soil nitrogen [132]. For example, the mineral fertilization of an apple (*Malus domestica*) orchard after replanting caused increased number of *Actinomycetes, Azotobacter*, proteolytic bacteria and phosphate-solubilizing bacteria [133]. Likewise, the use of inorganic fertilizers on a semi-arid alfisol led to an increase in the numbers of *Azotobacter*, even though the genetic diversity was unaffected [134]. Similar results were obtained in maize cultures [135] and in sugarcane cultures [136].

Chemical N addition was found to increase the relative abundance of oligotrophic bacteria and can have positive effects on some bacterial groups involved in C cycling such as *Ktedonobacteria* and *Acidobacteria* in extremely acidic subtropical forests [83].

On the other hand, intensive mineral N fertilization can negatively affect other specific bacterial groups (e.g., *Diazotrophs, Beta-Proteobacteria*) that are important rhizosphere microbes with symbiotic N-fixing interactions with leguminous plants.

The first step in nitrification (oxidation of ammonia into nitrite) is performed in soil by ammonia-oxidizing archaea (AOA) and AOB (*Beta*- and *Gamma-Proteobacteria*) [137]. AOA, which are 2- to 3000-fold more abundant than AOB in soils [137] and are key players in the N cycle in unfavorable environmental conditions (e.g., low nutrient content, low pH) [138], are more sensitive than AOB to different chemical fertilization treatments in acidic red paddy soil [138]. In this study, the AOA structure was more negatively affected. The long-term application of chemical NPK or N fertilizer has been found to significantly affect soil microbial communities throughout the soil profile and increase the relative abundance of AOA in surface soil (0–40 cm) only in the presence of additional organic fertilization (recycled crop residues or manure) [79,138]. This implies that the important ecological function of soil nitrification can be promoted only with simultaneous chemical and organic fertilization.

Phylogenetic analyses performed in a long-term organic and chemical fertilization experiment in a sandy loam soil in northern China indicated that *Proteobacteria* was the dominant taxonomic group in the soil, followed by *Acidobacteria* and *Gemmatimonadetes* [139]. In this study, long-term PK treatment was found to enhance bacterial richness and diversity more than NK, NP, NPK or organic manure addition. Da Silva and Nahas [140] found that the number of spore-forming Gram-positive rods was higher in plots with superphosphate.

Specific bacterial groups are enriched by organic fertilization, such as *Alpha-Proteobacteria*, *Gamma-Proteobacteria*, *Nitrospirae*, *Bacterioidetes* and *Actinobacteria* [141]. This was also found by Liang et al. [142], who studied the effects of different fertilization treatments (no fertilizer added, nitrogen fertilizer and bioorganic fertilizer) on the rhizosphere bacterial community. They found that the soil rhizosphere of winter wheat treated with bioorganic fertilizer had a higher microbial diversity than other treatments. The relative abundance of *Proteobacteria* in soil treated with bioorganic fertilizer was significantly higher than without fertilization, while *Acidobacteria* were significantly lower.

Summarizing the studies reported here, organic fertilizers increase soil organic matter and micronutrient contents, improve soil structure and promote a higher microbial diversity. Moreover, adding organic matter also favors the microbial activity that can be measured by dehydrogenase activity, related to soil quality. Finally, although depending on soil type, specific groups linked to fundamental nutrient cycling such as *Proteobacteria Firmicutes* are promoted by organic fertilization, probably because of both organic carbon improvement and the addition of specific microbial groups from the organic fertilizers.

In contrast, long-term N input by chemical fertilization not only decreases soil pH but also diminishes the relative abundances in particular microbial groups possessing genes related to P-solubilization. Moreover, the abundances in *Proteobacteria* such as *Alpha-Proteobacteria* and *Gamma-Proteobacteria*, together with some *Actinobacteria* containing genes coding for mineralize organic-P compounds in soils (e.g., alkaline phosphatase), are disadvantaged. Microbial groups related to nitrogen cycle (AOA and AOB) could be favored only with a combined chemical and organic fertilization.

3.4. Negative Effects of Chemical Fertilizers on Soil Ecosystem

The application of chemical fertilizers alone generally improves crop production; however, concerns have been raised not only about the severe environmental problems posed by such practices but also about the long-term sustainability of such systems [143]. It was also highlighted that synthetic fertilizers can increase disease incidence [144,145]. In some cases, the availability of some micronutrients (e.g., zinc) is reduced below the critical value, probably due to zinc precipitation by high concentrations of available soil P [146]. Long-term mineral fertilizer applications result in a significant loss in SOM, as found in monocultures performed for long periods without any addition of organic fertilizers and without crop rotation [90–92,147]. Mineral fertilization has also been found to cause decreases in porosity and nutrient availability of soil [110]. Moreover, mineral fertilization strongly affects the number of microorganisms and the qualitative selection of entire communities of soil microorganisms [59]. The study by Birkhofer et al. [148] indicates that the use of synthetic fertilizers and herbicides changes interactions within and between below- and above-ground components of the soil microbial community and ultimately increases the negative environmental impacts of agriculture by reducing internal biological cycles and pest control.

The long-term use of mineral fertilizers may be harmful, particularly at high rates of nitrogen fertilization, as it leads to increased gaseous nitrogen losses and to the deterioration of physical, chemical and biological soil properties [149,150]. Other studies (e.g., Doran et al. [59]) indicate that agricultural chemicalization, especially in the form of high rates of N fertilizer application on arable, grassland and horticultural soils, might not only risk the biological productivity and ecological stability of agroecosystems but also threaten surface and groundwater through the accumulation of nitrates, nitrites and many other organic nitrogen compounds [151].

Elevated concentrations of soil P have also been implicated in the P enrichment of shallow groundwater feeding coastal, lake and river ecosystems [152,153].

Fungi and their enzymes are less sensitive to the action of chemical fertilizers [154]. In particular, in the study by Marschner [155], only protease activity was affected by fertilization in the case of the enzymes studied.

Dangi et al. [156] suggested that the use of organic fertilizer or organic amendments can potentially mitigate the deleterious environmental impacts of inorganic fertilizers in agroecosystems, but they can also affect soil microorganisms that have not been well defined. They found that soil amendment such as biochar or the incorporation of other organic fertilizer for about two years affected microbial community biomass, composition and crop yield.

A possible combination of chemical and organic fertilization was found to be a good way to not only improve soil fertility, but also for enhancing crop yield, in particular for soils with low N, P and organic carbon content [157].

4. Some Consideration for Organic Amendments Used as Fertilizer

Organic amendments are defined as any materials originating from plants or animals and used for improving soil physical, chemical and biological properties, making a better soil quality for supporting plant productivity [8]. In fact, adding large nutrient quantities and exogenous microbes to soil can interfere with the indigenous bacteria growth, promoting the colonization of fertilizer-derived bacteria [158].

Long-term application of organic amendments in general improves soil fertility and soil structure, promoting the development of a beneficial soil microbiota capable of supporting high plant yield under intensive agricultural systems [159].

The most common soil organic amendments (Table 1) are animal manure [160–163], municipal biosolids [33], crop residues (forage or various crop varieties), compost and digestate. Some complementary fertilization options other than the use of chemical fertilizers include the use of bio-surfactants [164], biomineralization [165] and biofertilizers [166–168], including microbial suspension and seaweed concentrate [25,169,170]. The use of plant growth-promoting microorganisms [171] is a very promising tool that could also have positive effects by inhibiting pathogens through the production of antibiotics or cell wall lytic enzymes, inducing plant defence mechanisms [172].

Compost is derived from green waste or from sewage sludge [173]. Digestate can be derived from anaerobic digestion of several organic residues or organic wastes, including manure from farms, energy crops, municipal sewage sludge, biosolids and agro/food industry by-products [173].

Some organic amendments (manure, compost, digestate) could have some environmental side effects. For example, manure application can increase the abundance in soil of antibiotic resistance genes (soil antibiotic resistome) if the animals are treated with antibiotics for prophylaxis or therapeutic treatments [78]. Composting and anaerobic digestion has been suggested as a potential strategy to eliminate or diminish antibiotic residues and pathogens in livestock manure before its application as an organic fertilizer in agro-ecosystems [42,43,174].

Compost and digestate could also contain other contaminants in residual concentrations, such as heavy metals (e.g., nickel, lead, copper, zinc, mercury), although there are currently legislative limits for several compounds for the application of these organic amendments in agroecosystems [39].

5. Conclusions

Soil is of critical importance thanks to its role in several ecosystem functions, including food production. The soil microbial community has a crucial role in these functions. It also has a key role in the availability and accessibility of nutrients to plants and exerts plant bioprotection. Soil biochemical, microbiological and biological properties have been used for several years for estimating alterations in soil quality. However, the effects on soil microbial community and consequences on soil fertility have not been adequately studied at different levels. At the EU level, there is not currently a regulation regarding soil, and it is advisable that the microbial community should be considered and preserved.

Chemical fertilizers are sources of NPK nutrients in their inorganic forms and do not exert beneficial effects on soil physical properties (e.g., texture, structure, porosity, etc.) and SOM content. Absence of or leftover or incorrect addition of N, P and K fertilizers can affect the absorption and use of nutrients (including micronutrients), and because it negatively affects the beneficial plant rhizobacteria, it reduces crop yield and quality. Organic and synthetic fertilizers can affect microbial community compositions, favoring species functionally adapted to the nutrient inputs and activity and, ultimately, enhancing plant productivity. It is well known that chemical fertilizers can cause different environmental problems, including biodiversity loss, as highlighted by the new EU Soil Strategy for 2030, loss of SOM, deterioration of physical and chemical soil properties and, especially with long-term application, the lowering of soil fertility. Sustainable agriculture that limits chemical fertilization but also favors crop rotation, reduced soil tillage and extensified land use is an important global issue for preserving natural microbial communities (in terms of species abundance and richness of specific beneficial microorganism groups in soil), maintaining their ecological function and sustaining soil fertility.

Because it is not reasonable to use only organic amendments to support plant productivity since they do not provide high amounts of NPK, a combined addition of chemical and organic fertilizers could be the right solution, particularly for soils with low N, P and organic C contents. In particular, the so-called 4 Rs for nutrient management, i.e., "right source, right rate, right time and right place" could be the correct path for farmers to manage fertilization of soil. Considering that, each basic element (N, P, K) has to be applied with a balanced fertilization by organic (including bio-organic) and synthetic fertilizers considering the soil needs; the role of micronutrients is also fundamental (for example in stimulating the availability of P). In any case, because the fertilization strategy is frequently related to economic rather than agronomic evaluations, N and, to a lesser extent, P are the only nutrients used and K fertilization is underexploited, so there is still a widespread unbalanced fertilization. A combined fertilization with chemical and organic fertilizers (in particular with compost, digestate or plant residues) could be a good compromise for providing basic elements together with micronutrients and improving soil organic carbon and increasing several physico-chemical soil properties. The new era in the use of plant-growth-promoting microorganisms can lead to a decrease in use of chemical fertilizers, although this practice still needs to better investigated and adapted to specific soils and plant cultivations. Finally, it has to be taken into account that the EU Fertilizing Products Regulation (Reg. 2019/1009 EU), which governs the production and addition to agroecosystems of organic and inorganic fertilizers, organo-mineral fertilizers, soil improvers, liming materials, plant biostimulants, inhibitors, and fertilizer products, will be implemented in 2022, and the fertilizing product quality certification process will be harmonized across the EU.

Any improvement in plant quality (e.g., genetically engineered crops able to form nitrogen-fixing symbioses and fixing nitrogen without microbial symbionts) avoiding or reducing the use of mineral fertilization also has to be promoted.

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