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Review

Sustainable Agricultural Systems for Fruit Orchards: The Influence of Plant Growth Promoting Bacteria on the Soil Biodiversity and Nutrient Management

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Abstract: Awareness towards the loss of soil quality as well as consumer perception about the environmental impact of agricultural activity have stimulated research and government activity toward the implementation of a sustainable agricultural system. The European Commission, in the next funding program, established specific objectives to promote the conversion towards a more environmentally sustainable agricultural system through its Green Deal Strategy. The demand for ecologically and sustainably cultivated fruits increases every year; however, suppressing such demand is necessary to improve the production performance of orchards. The sustainable management of orchard production requires combined knowledge from different fields. The key challenge is to design orchard systems that can integrate sustainable practices, nutrient cycle knowledge and promotion of soil biodiversity. Therefore, this review compiles works that address the challenges in the implementation of a sustainable agriculture system based on Plant Growth-Promoting Bacteria (PGPB) and their impact on soil biodiversity as well as that of nutrient management on the development of fruit orchards.

Keywords: sustainability; orchards; PGPB; nutrient management; agriculture

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1. Introduction

Chemical inputs have driven the productivity of the agricultural sector over the final part of the last century. Such overuse has led to a theoretical limit of agrochemical efficiency, a point from which further application does not directly correspond to further crop yield increments [1].

The pursuit for boosting agricultural yields, to supplement ever-increasing food demand from a rising human population, had progressed to an imbalanced application of agrochemicals to overcome the reduced crop production at higher costs. As a consequence, production costs increased to overcome the reduced crop yield as well as alterations of soil properties, such as its physical, chemical and biodiversity characteristics. The progress of these alterations could disrupt fundamental services provided by the soil ecosystem, such as the water cycle, nutrient cycle, or climate regulation [2]. To overcome the rising environmental and climate problems, there is an incremental effort to develop efficient solutions in all economic activities, including agriculture. Awareness of soil ecosystem importance and associated problems has increased since the beginning of the XXI century (2002) through several initiatives from the Food and Agriculture Organization (FAO) and the United Nations (UN), such as the International Initiative for the Conservation and Sustainable Use of Soil Biodiversity. The peak of such campaigns was achieved with the declaration of the United Nations Decade on Ecosystem Restoration (2021–2030) and the release of the UN–FAO report, the State of Knowledge of Soil Biodiversity [3,4].

In the case of the European Union (EU), similar concerns have been part of agricultural policies for example, the Common Agricultural Policy (CAP) and investment initiatives programs (e.g., Horizon 2020) [5]. More recently, to overcome climate challenges, as well as to protect and improve natural capital and citizens' health, the EU has released its plan to improve sustainability in all economic sectors: the European Green Deal Strategy. At the center of the plan is the Farm to Fork strategy and Biodiversity Policy for 2030, where the need is emphasized to improve the balance between biodiversity and food systems to increase competitiveness and resilience [6]. Implementing the European Green Deal strategy will generate challenges and opportunities. Even though strategies of appropriate production practices and sustainability programs have been in place for years, large-scale adoption is still lacking. Beliefs about the high costs of sustainable approaches over the expected return in the medium and long term, as well as the lack of knowledge of some producers about the correct implementation of such approaches, could hinder the Green Deal's implementation [6,7].

The objective of this work is to review information on the state of sustainable management approaches for the implementation of sustainable agriculture systems based on Plant Growth-Promoting Bacteria (PGPB), and their impact on soil biodiversity and nutrient management on fruit orchard development, addressing innovative practices, nutritional management and soil biodiversity protection.

2. Sustainability Concept

Sustainability definition is a difficult endeavor due to the need to reflect and integrate multiple goals, values and priorities that shift over time. Difficulty in defining it is also one of the reasons for discord and ineffective implementation. However, the current perception of the sustainability concept is based on three pillars: economic, environmental and social. Even though other dimensions are commonly considered (e.g., institutional, political, and ethical), it is recognized that they are interdependent and interlinked, as shown in Figure 1 [8,9].

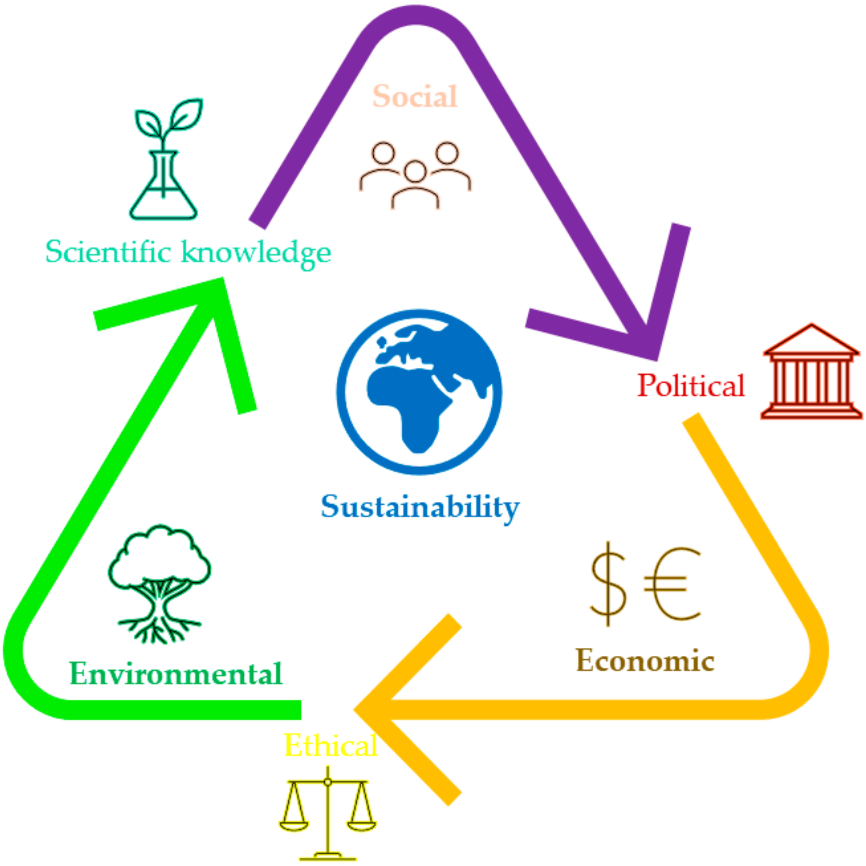

Figure 1. The core concept of sustainability and the interactions between the different dimensions.

Trigo et al. (2021), identified in the literature two main interpretations of sustainable agriculture. One is described as a philosophical base, focused on the goal of embracing alternative methods to diminish the impact of agricultural activities, with the distortion of circular perspective and no clear approved alternative. The other approach is sustained by a set of goal-oriented strategies, based on scientific knowledge, practices, technologies, or policies (e.g., mimic nature, regenerative and circular approach) [9]. This last conceptualization is the base of the future vision stated in the 2030 Agenda for Sustainable Development, in which concern for the environment occupies a central role [9].

Sustainable food production in agriculture is an extensive process based on alternative approaches to industrial agriculture management, which depend on the increment of production yields using agrochemicals for nutrient inputs and pest controls. Sustainable agriculture is supported by new technical developments and management, highlining the need for more attention on environmental protection [8]. The main objective is to fulfill food human requirements, reducing the negative burden on the environment and its resources through management of soil fertility and its physical–chemical properties, using a regenerative approach, while improving or maintaining economic viability [10,11]. Therefore, for an efficient implementation of a sustainable food system and the establishment of specific targets, evaluation parameters, and proper assessment tools are necessary to sustain further policy changes, and support the transition to sustainable practices.

The following chapters will be discussed some topics for a sustainable agriculture system. Specific attention will be given to the nutrient cycle, sustainable management practices, and the impact of biodiversity on the soil.

3. Sustainable Agriculture Systems

Terrestrial ecosystems have as their basis the natural complex dynamic of soil structures. Its biological (e.g., soil biodiversity), chemical (e.g., nutrients cycle), and physical properties (e.g., bulk density, porosity) are important prerequisites to support plant growth. Awareness of the interactions between all properties in an ecological cycle is the basis of sustainable agriculture. Therefore, indices of soil health should integrate the examination of all soil properties essentially to achieve an understanding of soil quality [1].

Sustainable principles are of utmost importance when applied to orchards, since they also have interesting features for a balanced ecosystem service; for example, the contribution of biodiversity, the impact of carbon sequestration, or water regulation [12].

3.1. Sustainable Practices

Sustainable practices are a set of medium- and long-term strategies based on ecological cycles to maintain soil functions and services, as well to provide economic crop production and ecological protection. Nevertheless, the sustainability of the system is more dependent on the choice of management practices other than the farming structure. Alternative practices generally diverge from conventional operations, in the intensity and quantity of soil manipulations as well the nature of nutritional inputs (e.g., large volumes of agrochemicals nutrients vs. organic amendments) [13,14]. Table 1 represents some of the most utilized management practices and sustainable systems. The described approaches also contribute to pest management. Sustainable pest management and weed control are linked with cropping techniques (e.g., rotation, seeding timing, or flaming), biological control and natural pesticides (e.g., plant extracts).

Table 1. Description of the main sustainable practices and systems.

	Description	**Examples of Expected Impact**	**Reference**
Management Practices			[15–17]
Cover crops and green manure	Provide constant soil cover.	Increase SOM; nutrient mobilization; decrease emergence of pests and pathogens.	
Crop rotation	Sequence of different crops cultivated on the same land, with different temporal frames.	Use of different soil nutrient combinations to avoid over-exploiting the soil ecosystem.	
Reduced tillage	Reduce mechanical disturbance of the soil.	Avoid soil parameters degradation (e.g., carbon sequestration, soil density, water holding capacity).	
Intercropping	Cultivating different crops species on the same field simultaneously.	Improve nitrogen fixation and other nutrient cycles; obtain soil cover; decrease emergence of pests and pathogens.	
Structural elements	Features in the landscape and techniques implemented or managed by the farmer.	Decrease impact of weather; improve light accessibility.	
Irrigation management	Control the amount of water supplied.	Maintain optimal humidity levels; avoid nutrients leaching; decrease water loss.	
Allowed External Inputs			
Organic fertilizer	Application of animal manure.	Supplement the Orchard with the required nutrients; improve soil quality.	
Compost	Aerobically decomposed organic matter		
Vermicompost	Organic material decomposed by earthworms.		
Biofertilizers	Growth-promoting bacteria or fungus.		
Fertigation	Water fortified with nutrients and controlled administration.		
Sustainable Agriculture Systems			
Conservation Agriculture	Combination of three principals 1. Minimal mechanical soil disturbance 2. Permanent soil cover by crop residues, cover crops and mulching. 3. Diverse crop rotation or mixture.		
Crop-Livestock systems	Integration of crops with live stocks.		
Organic Agriculture	Absence of agrochemical inputs, relying on ecological processes and biodiversity.		
Agroforestry	Integrations of trees and crops in the same land. Integration of woody and herbaceous layers.		

Several studies have evaluated the efficiency of sustainable management practices as the pros and constraints of such practices [15–19]. The antagonism between the conventional and sustainable approaches is centered on maximizing economic growth, protecting the environment and providing adequate metrics for evaluation to support evidence of the unsustainability of industrial agriculture and that alternative approaches can achieve adequate yields [20]. On the encouraging side, organic tactics serve higher ecological outcomes, improve soil quality, increase profitability, and present higher nutritional value. On the adverse side are higher costs and prices and lower yields [16]. Furthermore, other factors that influence the adoption of or enrollment in sustainable practices by the farmers were reviewed by Liu et al. (2018) [21]. According to Liu et al., the farmers' knowledge is acquired as a temporally dynamic learning process, divided into four stages: (1) awareness—they become conscious about the alternative approaches and potential relevance to them. (2) Interest—collection of information about the practices. (3) Trial and evaluation—application on smaller portions of terrain, evaluation of the results and skills development. (4) Adoption and adaptation—the decision to scale up and customize practices in the fields. Among the main attributes that influence this process are farmers' characteristics (e.g., age, experience, education, heritage, "lifestyle" and environmental consciousness), farm traits (e.g., size, soils, land tenure, type of production) and financial motivation (government subsidies, farm income and off-farm income). Other uncertain associated factors are related to peer pressure, social norms, geographic regions, policies and markets [21].

3.2. Nutritional Management

Nutrient management considers the estimation of nutrient budgets. This means integrating knowledge about the soil's nutrient capacity and crop nutrient needs and quantifying the amount of nutrients present in inputs (e.g., manure) to avoid the application of disproportionate nutrient concentrations to the plants and soil. In the case of orchards, nutrient application should be performed cautiously before and after harvest [22]. Nutrients are biochemical elements with organic or synthetic origins that are used by plants and other organisms for their development. For fruit orchards, such nutrients also have a significant role in fruit development [23], nutritional value [24] and pest control [25].

Nutrient deficiency may result in decreased plant quality and/or productivity. It also can induce an imbalance of overall biodiversity since plants reinforce above-ground and below-ground food webs. In addition, appropriate nutrient concentration up to the tolerance levels stimulates the absorption of other nutrients (synergism). The occurrence of excess levels of a particular nutrient may inhibit the accumulation of others (antagonism). Therefore, is necessary to improve plant nutrient efficiency, which requires knowledge about how they are used by the plant considering the development stage of the plant/tree and species specificity [26].

The nutrient cycle refers to the transformation of compounds from the original bedrock and soil organic matter decomposition (SOM), into simple molecules that are assimilable by several organisms and plants. SOM is a complex element of soil because it consists of several carbon sources (e.g., plant, microbial, and animal bodies) in diverse disintegration stages and provides a mixture of heterogeneous macro and micro, organic and inorganic constituents. Therefore, it is an integrated part of the nutrients cycle, with benefic effects on soil properties and consequently on plant development [27]. Factors that influence the nutrients availability and accessibility for plants uptake are climate (e.g., temperature), soil physical properties (e.g., texture, structure, moisture), and chemical parameters (e.g., pH, SOM). Furthermore, nutrient use efficiency is influenced by cover plant chemical composition, as well as the taxonomic and functional diversity of soil biodiversity (e.g., microorganisms) [4]. The soil nutrient pool includes macronutrients as well as micronutrients. The macronutrients are constantly referred to as the most important in any crop or orchard system, due to their impact on plant growth and production. They are represented by nitrogen (N) [28,29], potassium (K) [30,31] and phosphorus (P) [32]. Others that are required but possess a secondary degree of importance are calcium [33], magnesium and sulfur [34]. Table 3 summarizes the impact of the main macronutrients on plants. Micronutrients, for example iron (Fe) or boron (B), are required as cofactors for enzyme activity, and other biological functions as summarized in Table 4.

Knowledge about the nutritional needs of plants is important for an efficient administration not only of the nutrients but also of the adopted management practices. The analysis of plant nutritional status can be achieved by four different approaches: (i) foliar symptoms; (ii) plant tissues analysis; (iii) soil analysis; (iv) biological tests of higher plants or microorganisms. None of the previous approaches should be taken as the optimal method, but should be considered as supplements to each other. Table 2 presents the leaf nutritional requirements in different fruit orchards. The nutritional deficit may be caused by more than one nutrient or be driven by the excessive quantity of other nutrients. In addition, damage originating from disease, herbicide or insects can cause similar symptoms to macronutrient or micronutrient deficiency or excess. Therefore, the inclusion of soil and water analysis should be included to assist in proper management decisions [35].

3.3. Plant Growth Promoting Bacteria (PGPB)

The biological diversity of soil is important to regulate the nutrients cycle and physical properties of the soil, which also influence the provided ecosystem services (e.g., nutrient cycle, water-holding, CO_2 sequestration) [52]. The soil is a complex and heterogeneous system, comprising organo-mineral aggregates of different sizes and organic components that create habitats for soil biodiversity across multiple spatial scales; the diversity in habitat composition with pores of different sizes filled with air and/or water allows an incredible number of taxa of different sizes and ecology to inhabit it. Soils are one of the main reservoirs of biodiversity, arranged in a complex heterogeneous system. They can be characterized by size fraction and functional importance [4].

Microbes with a size range of 20 nm to 10 µm (e.g., virus, bacteria, Archaea, fungi) and Microfauna 10 µm to 0.1 mm (e.g., soil protozoa and nematodes) inhabit soil. Their main functional activity encompasses the decomposition of soil organic matter into several macronutrients and micronutrients [53]. Mesofauna range in size between 0.1–2 mm and encompass microarthropods (e.g., mites). They boost the soil's active biochemical interactions, participating in litter transformation/fragmentation, creating new surfaces for microbial attack [4]. Macrofauna, from 2–20 mm, include large invertebrates (e.g., earthworms). They actively participate in litter transformation and predation, while some are plant herbivores or modify soil structure, improving the energy and nutrient flux [54]. Megafauna (>20 mm) are vertebrates (e.g., Mammalia, reptilians and amphibia). They generate soil spatial heterogeneity as alterations in its profile through movement [4]. As a resume, Figure 2 represents the integration of the interactions between PGPB, soil characteristics; plants/tree mechanisms and biodiversity, to plant sustainability [11,24,55].

Among the described taxa, microorganisms have been gathering increasing interest and efforts in scientific works as biofertilizers. They have been recognized as an important influence on nutrient accessibility, uptake efficiency, and the ability to recover soil health and status. Biofertilizers are agricultural supplements that contain live or dormant microorganisms that assist the overall plant growth and yield increments in an eco-friendly way. The main constituent of biofertilizers is root-colonizing bacteria thriving in the plant rhizosphere and bulk soil. They are frequently denominated as Plant growth-promoting bacteria (PGPB). They are common facilitators of plant accessibility to nutrients, and endurance facing biotic and abiotic stresses [10,56].

Table 2. Nutritional requirements of some fruit trees.

Nutrients	Kiwi			Apple			Peach and Plum			Pomegranate			Citrus		
	Deficit	Normal	Excess	Deficit	Normal	Excess	Deficit	Normal	Excess	Deficit	Normal	Excess	Deficit	Normal	Excess
N	-	23–28 [e]	-	<1.6 [a]	2.0–2.4 [a]	>3.0 [a]	1.7	2.4–3.0	4.0	-	>2.0	-	<2.2 [a]	2.5–2.7 [a]	>3.0 [a]
P	-	1.6–2.0 [e]	-	<0.10 [a]	0.15–0.20 [a]	>0.3 [a]	0.09	0.14–0.25	0.4	-	0.13–0.15	-	<0.09 [a]	0.12–0.16 [a]	>0.30 [a]
K	-	12–19 [e]	-	<0.8 [a]	1.1–1.5 [a]	>2.0 [a]	1.0	1.6–3.0	4.0	-	1.0–1.2	-	<0.7 [a]	1.2–1.7 [a]	>2.4 [a]
Ca	-	33–44 [e]	-	<0.7 [a]	1.1–2.0 [a]	>2.5 [a]	1.0	1.5–3.0	4.0	-	4.5–4.9	-	<1.5 [a]	3.0–4.9 [a]	>7.0 [a]
Mg	-	4.0–11 [e]	-	<0.18 [a]	0.25–0.35 [a]	>0.5 [a]	0.2	0.3–0.8	1.10	-	0.38–0.42	-	<0.2 [a]	0.30–0.49 [a]	>0.7 [a]
Cl	-	6.0–10 [e]	-	-	<0.4 [a]	>1.0 [a]	-	-	-	-	-	-	-	0.05–0.10 [a]	>0.25 [a]
Na	-	<500 [b]	-	-	<0.02 [a]	>0.5 [a]	-	-	-	-	-	-	-	-	>0.25 [a]
Mn	-	44–173 [b]	-	<20 [c]	25–100 [c]	>200 [c]	20 [c]	40–160 [c]	400 [c]	-	30–45 [d]	-	<17 [b]	25–100 [b]	>300 [b]
Zn	-	26–44 [b]	-	<10 [c]	16–50 [c]	>50 [c]	15 [c]	20–50 [c]	70 [c]	-	14–15 [d]	-	<17 [b]	25–100 [b]	>300 [b]
Cu	-	7.0–22 [b]	-	<4 [c]	6–20 [c]	>21 [c]	4 [c]	4–16 [c]	30 [c]	-	4.5–7.0 [d]	-	<3 [b]	5–16 [b]	>20 [b]
Fe	-	90–268 [b]	-	-	>50 [c]	-	60 [c]	100–250 [c]	500 [c]	-	70–85 [d]	-	<35 [b]	60–120 [b]	>200 [b]
B	-	39–80 [b]	-	<15 [c]	20–60 [c]	>200 [c]	20 [c]	25–60 [c]	80 [c]	-	20–22 [d]	-	<20 [b]	36–100 [b]	>200 [b]
Reference		[47]			[48,49]			[22,50]			[26,51]			[35]	

[a] Dry weight %; [b] mg/kg; [c] ppm; [d] mg/L; [e] g/kg.

Table 3. Main macronutrients and their influence on plants.

Nutrients	Uptake Form	Soil Conditions	Biological Functions	Plant Impact/Deficiency	Stratification	References
Nitrogen (N)	NH_4^+	Low pH and reducing soil conditions.	Contribute to amino acid formation; energy homeostasis, signaling and protein regulation. Essential for co-enzymes, photosynthetic pigments, secondary metabolites and polyamines.	Stunted growth, small leaves, reduced shoot branching and early flowering. Often anthocyanosis on leaf and stem.	acropetal	[31,33,34,36–40]
	NO_3^-	Higher pH and aerobic conditions.				
Phosphorous (P)	$H_2PO_4^-$	Available form is pH dependent. Natural availability is very slow. Uptake is improved by the presence of mycorrhizal symbioses.	Cellular energy homoeostasis; component of nucleic acids; structural role in cellular membranes; reversible protein phosphorylation; cellular metabolism.	P deficiency causes a rapid decrease in photosynthetic rates. Anthocyanosis. Dark-green and/or purple leaves.	Acropetal	
Potassium (K)	Other forms: solution K, exchangeable K, “fixed” K, structural K in primary minerals	K^+ is dehydrated and coordinated with oxygen atoms not available to plants. K solubilization is driven by water.	Metabolic reactions and enzyme activity. Ribosome mediated protein synthesis. Accumulation of reducing sugars and depletion of organic acids; turgor provision and water homeostasis. K demand is strongest during fruit development.	Accelerate premature leaf senescence and reduce numbers of flowers and fruits in subsequent years. Chlorosis on tip of oldest leaves that develop into marginal necrosis. Bronzing. Slack appearance due to poor turgor and stomatal control.	Acropetal	
Calcium (Ca)	Ca^{2+}	Ca^{2+} adsorbed to colloids can be exchanged with the soil solution where much of the ‘free’ Ca^{2+} forms nearly insoluble compounds with other elements such as phosphorus, thus making P less available.	Structural and secondary messenger. Rigidity to cell walls and membrane structure.	Ca^{2+} levels may fall below a critical level in fast-growing tissues causing diseases such as ‘black heart’ in celery, ‘blossom end rot’ in tomatoes or ‘bitter-pit’ in apples. Disintegration of root tissue. Necrotic lesions on leaf edges and tips. Meristem death. Necrotic spots on fruits and vegetables. Leaf deformity.	Basipetal	
Magnesium (Mg)	Mg^{2+}	Adsorption to soil particles is relatively weak which results in high leaching rates and Mg^{2+} deficiency is therefore common.	Central position in the chlorophyll molecule; signal element in chloroplast development; roles as enzyme cofactors associated with energy transfer.	Intravenous chlorosis on oldest leaves that eventually develop into necrosis. Accumulation of sucrose and starch in chloroplast.	Acropetal	
Sulfur (S)		In saline and sodic soils, inorganic salts are predominant.	Amino acids; protein activity reductant in the detoxification of reactive oxygen species.o	Chlorosis of young leaves. Stunted growth. Anthocyanosis; S toxicity is rare but can occur in saline soils with high levels of SO_4^{2-} salts, and atmospheric pollution.	Basipetal	
	SO_4^{2-}	In aerobic conditions.				
	FeS, FeS_2 and H_2S	Reducing environment created by flooding.				
	SO_4^2 and H_2S.	Extracted from atmosphere.				

Stratification: Basipetal, symptoms first appear on youngest leaves; acropetal, symptoms first appear on oldest leaves. NH_4^+—ammonium cation; NO_3^-—Nitrate; $H_2PO_4^-$—Dihydrogen phosphate; SO_4^{2-}—Sulfate; FeS—Iron sulfide; FeS_2—Iron disulfide; H_2S—Hydrogen sulfite.

Table 4. Micronutrients and their influence on plants.

Nutrient	**Soil Availability**	**Biological Function**	**Deficiency**	**Stratification**	**Reference**
Iron (Fe)	Maximum availability in acidic pH range and decreases drastically with increase in pH. Excessive water and poor aeration, organic matter, interaction with other nutrients effect control Fe availability.	Synthesis of chlorophyll	Leaves exhibit pale color and veins remains green or interveinal chlorosis of the whole leaves. Papery white color of the leaves occurs under severe deficiency.	Basipetal	[41,42]
Manganese (Mn)	Soluble Mn (Mn^{2+}) is rapidly converted to plant-unavailable Mn oxides, particularly in sandy alkaline soils. Disorder in soils with high pH and high partial pressure of O_2.	Enzyme activity. Oxidation-reduction processes. Synthesis of chlorophyll,	Similar to Fe deficiency, with pale leaves and green veins. Sometimes brown, black or grey spots are observed next to leaf veins. Chlorosis up to leaf margins followed by browning and necrosis.	Acropetal	[41,43]
Zinc (Zn)	Low content in the rocks/minerals, soil pH, presence of calcium carbonate, soil redox potential, clay content, soil moisture status. Positive interaction with nitrogen (N) and potassium (K). Negative interactions with phosphorus (P), calcium (Ca), iron (Fe), and copper (Cu).	Regulation of plant growth and transformation of carbohydrates. Required for nucleic acid synthesis and enzyme activation	Interveinal chlorosis	Basipetal	[41,42]
Copper (Cu)	Availability decreases with high pH, high soil organic carbon and high clay content	Enzyme system that utilizes carbohydrates and proteins and is important for reproductive growth.	Dieback of shoot tips; old leaves develop brown spots. Male flower sterility, delay flowering and senescence.	Acropetal	[41,44]
Boron (B)	Increasing soil pH decreases B availability by increasing B adsorption onto clay and Al and Fe hydroxyl surfaces, especially at high soil pH	Required for nucleic acid synthesis, pollen germination and the growth of the pollen tube. Promotes root development, enzyme activity, lignin synthesis, sugar transport, seed and cell wall formation, calcium uptake and water relations. Imparts drought tolerance to the crops	Curled, brittle leaves; discolored or cracked fruits. Leaf symptoms found on leaf tips and terminal buds or the youngest leaves, which become discolored and may die under acute deficient conditions. Development of water-soaked areas on the leaves, development of corky tissues and purpling or yellowing of interveinal portion of young leaves.	Basipetal	[41,45,46]

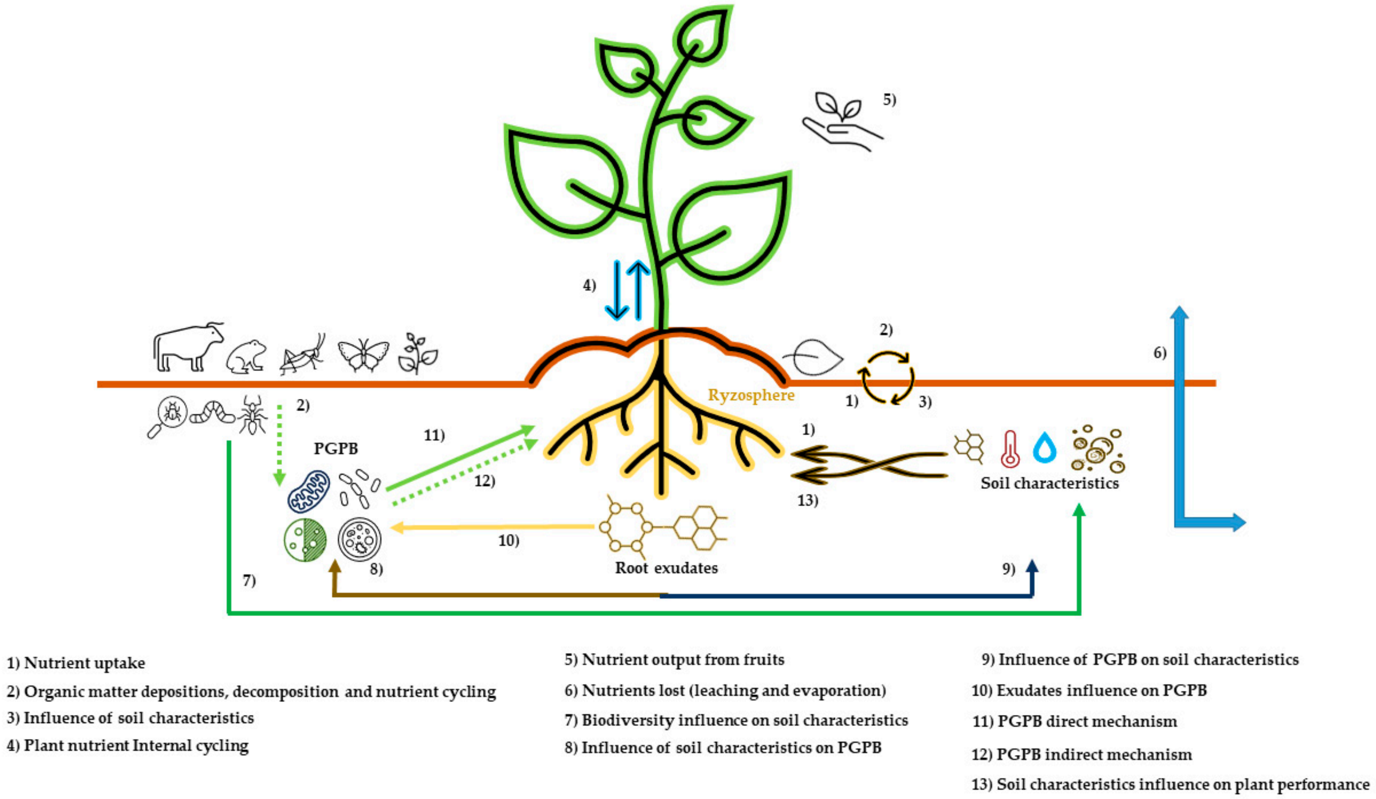

Figure 2. Overall visualization of the interconnections between different components in a soil ecosystem.

Most of the PGPB are found in the plant rhizosphere, which is a constricted zone of soil contiguous to the plant root system. This zone, which displays essential ecological functions is colonized by prokaryotes (e.g., archaea, and viruses) and eukaryotes (e.g., fungi, algae). All of the present taxa are potential biofertilizers or important constituents of plant biostimulants [57]. The rhizosphere-specific ecosystem is supported by the synergetic effect of root exudates (e.g., carbohydrates lipids, or amino acids) and soil properties (e.g., pH, bulk density, aeration or water-holding), which directly or indirectly assist in growth promotion and stress management.

The most common bacterial strains used and studied as biofertilizers or soil amendments are: *Bacillus* sp.; *Agrobacterium* sp.; *Pseudomonas* sp.; *Arthrobacter* sp.; *Streptomyces* sp.; *Sinorhizobium* sp.; *Serratia* sp.; *Azospirillum* sp.; etc. Table 5 shows some recent studies, with applications of PGPB in different fruit orchards. The most common fields of study are disease tolerance, growth performance, fruit yield and nutrient uptake. The interactions between PGPB and plants rhizomes are commonly divided into two mechanisms, direct and indirect processes, that have been the target of several reviews [25,56,58–61]. Direct mechanisms encompass the processes that have a direct influence on plant performance, among which are: Biological nitrogen fixation; Mineral solubilization/mobilization (e.g., K, P, Zn); and plant growth regulators (e.g., auxin or gibberellin). Indirect mechanisms are related to antagonist activity against pests and pathogens. It also comprises the formation of volatile organic compounds, antibiotics, or biosurfactants, induced systemic resistance, and stress tolerance [25,56,58–61].

Table 5. PGPB studies on fruit orchards.

Fruit Crop	**Microorganisms**	**Parameters Evaluated**	**Reference**
Apple	*Azotobacter chroococcum*, *Bacillus subtilis*, *Bacillus megaterium*	Fruit yield, Nutrient efficiency	[62]
	Bacillus spp., *Burkholderia* spp., *Pseudomonas* spp.	Growth, Fruit yield	[63]
	Pseudomonas putid, *Bacillus subtilis*	Foliar application	[64]
	Alcaligenes spp., *Agrobacterium* spp., *Staphylococcus* spp., *Bacillus* spp., *Pantoea* sp.	Iron acquisition	[65]
	Pseudomonas fluorescens	Drought stress, Nutrient uptake, root grow	[66]
	Bacillus sp., *Bacillus amyloliquefaciens*, *Paenibacillus polymyxa*	Nutrient composition of apple leaves	[67]
	Bacillus amyloliquefaciens	Growth	[68]
	Pseudomonas aeruginosa, *Pseudomonas fluorescens*, *Pseudomonas putida*	Soil properties; Nutrient availability	[69]
	Bacillus subtilis; *Streptomyces* spp.	Nutritional status; Growth	[70]
Pomegranate	*Azotobacter chroococcum*	Plant canopy, Pruned material, Fruit yield	[71]
Plum	*Pseudomonas stutzeri*; *Bacillus toyonensis*	Growth; Acclimatization; Disease tolerance	[72]
	Pantoea agglomerans	Fruit traits; Chemical composition	[73]
	Pseudomonas fluorescens; *Pantoea agglomerans*	Rootstock growth	[74]
Peach	*Bacillus flexus*	Disease tolerance; Growth	[75]
	Alcaligenes sp., *Agrobacterium* sp., *Staphylococcus* sp., *Bacillus* sp. and *Pantoea* sp.	Iron acquisition	[76]
	Azospirillum sp.; *Frateuria aurantia*; *Bacillus megaterium*	Nutrient uptake; Growth	[77]
	Bacillus subtilis; *Bacillus tequilensis*; *Bacillus methylotrophicus*	Disease tolerance	[78]
	Alcaligenes spp., *Agrobacterium* spp., *Staphylococcus* spp., *Bacillus* spp. and *Pantoea* spp.	Growth and Nutrient content	[79]
Avocado	*Paraburkholderia* sp.	Growth; Nitrogen acquisition,	[80]
	Pseudomonas sp., *Serratia* sp. and *Stenotrophomona* sp.	Disease tolerance	[81]

Table 5. *Cont.*

Fruit Crop	**Microorganisms**	**Parameters Evaluated**	**Reference**
Kiwi	*Pseudomonas bijieensis*	Disease tolerance	[82]
	Bacillus amyloliquefaciens, *Bacillus pumilus*, *Bacillus circulans*,	Growth promotion; Nutrient uptake	[83]
	Paenibacillus polymyxa; *Comamonas acidovorans*, *Bacillus* sp.	Root growth	[84]
	Agrobacterium rubi	Root growth	[85]
	Bacillus subtilis, *Bacillus stearothermophilus*, *Bacillu amyloliquefaciens*, *Actinobacteria* sp.	Impact on soil nutrients	[86]
	Azospirillum actinidiae	Nitrogen fixation	[87]
Citrus	*Bacillus* sp.; *Lactic acid bacteria*; *Actinobacteria* sp.;	IAA production; Nutrient availability	[88]
	Pseudomonas putida; *Novosphingobium* sp.	Salt stress	[89]
	Enterobacter hormaechei; *Enterobacter asburiae*; *Enterobacter ludwigii*; *Klebsiella pneumoniae*	Growth performance	[90]
	Methylobacterium sp.	Rootstock development	[91]
	Serratia marcescen	Disease tolerance; Growth promotion	[92]
	Bacillus velezensis, *Pseudomonas aeruginosa*	Disease tolerance	[93]
	Rhodococcus sp., *Burkholderia* sp.	Disease tolerance; Growth promotion	[94]
	Bacillus sp., *Lactobacillus* sp., *Streptomyces* sp., *Methylobacterium* sp., *Hymenobacter* sp., *Pantoea* sp., *Curtobacterium* sp., *Spirosoma* sp.	Disease tolerance	[95]

IAA—indole acetic acid.

In Table 5, specific examples of the application of PGPB in fruit orchards can be found, for different species. In the case of apples according to Kuzin et al., 2020, fruit yield (kg tr^{-1}), was improved when PGPB was applied (12–13%), in comparison with the control (11%) [62]. Thokchom et al., 2014, applied PGPB to citrus plant and evaluated the growth, registering an increase on plant height (40–55 cm) when compared with the control (31 cm) [90]. Another area of investigation is disease tolerance, as studied by Ali et al., 2022. In this work the application of PGPB reduced necrosis symptoms caused by PSA (*Pseudomonas syringae* pv. *actinidiae*) in 92% of kiwi leaves after 10 days [82]. Gani et al., 2021, studied PGPB's effect on pesticide stress tolerance on peach, detecting the degradation of different concentrations of chlorpyrifos within 30 days, accompanied by the increased production of antioxidants and exopolysaccharides [75]. These examples demonstrate the capability of PGPB when applied in fruit orchards, with promising results.

However, the development of new bio inoculants, their large-scale production and field application have to address specific PGPB characteristics and overcome several operational constraints to improve its efficiency and effectivity (Figure 3). The mere use of primary screening strategies to obtain culture isolates for PGPB traits could result in isolates that perform well in the laboratorial environment but may not be efficient under field application. On the other hand, the discarded colonies might possess different strategies, more suitable to a specific environment due to different mechanisms of action, and be rejected. This might occur because they are not recognized by the standard screening conditions, which might not be suitable to recognize such different approaches. In the case of operational constraints, they consist mostly of required investment, the equipment needed and essential know-how to achieve the mandatory product quality and performance [2,96].

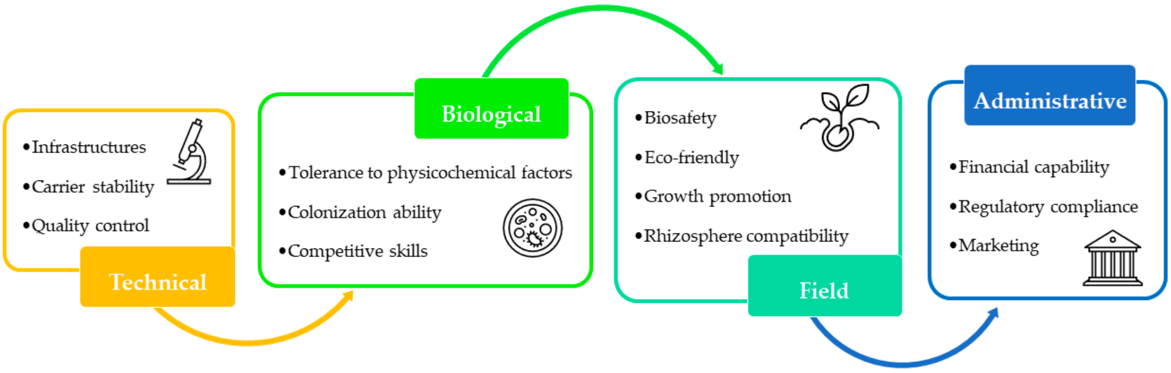

Figure 3. Common desirable features that are targets of study to overcome frequent hurdles.

4. Future Prospects

Ecological innovation triggered by chemical or physical engineering is achieving its maximum development, not only because of resource over-supplementation, but also due to the practical hurdles, difficulties in crop yield improvement and economic challenges. The continuous use of conventional farming practices might not be sufficient to achieve the necessary yields from crops and orchards needed to feed the ever-growing human population. To alter such a situation, it is necessary to readdress attention to soil health and to the services provided by the ecosystem, as means to accomplish the sustainable development of agricultural practices. For that, a change of agricultural paradigm, to a system based on soil-plant–bacterial interactions, is necessary to restore soil health and quality [71].

It will also be necessary to bridge the knowledge from basic, applied research and field experience, to achieve a fundamental understanding of the complex interactions between soil, plants and PGPB. The present knowledge perspective indicates the use of microorganisms as soil inoculants and eco-friendly fertilizer, to improve soil quality and plant efficiency. However, microorganisms are more effective when adequate conditions are provided, to achieve maximum metabolic efficiency (e.g., water, pH, oxygen, or temperature). Future advances on the knowledge of mechanisms of PGPB action will open new windows to project strategies to increment biofertilizer efficiency [14].

In the specific case of sustainable orchard systems, further knowledge is necessary on plant nutrient dynamics (e.g., carryover effects from remobilization) as well on soil and root dynamics to provide new management techniques, enhance fruit quality and productivity. The development of specific rootstocks and tree species suitable for sustainable systems is required [36].

Another important field of action is the discussion of proposals and public policies to promote the conversion to sustainable management practices to support the costs and hurdles of the transition from conventional agriculture [21].

Simultaneous and concerted efforts between the previously described topics are a requirement for well-established integrated soil management practice. Besides such integrated visions still being in their first steps, they has the potential to transform actual sustainable practices into a much more efficient system in terms of biodiversity protection and the production of sustainable agriculture systems for fruit orchards.

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