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Review

Mediterranean Intercropping Production Systems: Challenges and Opportunities

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Abstract

Intercropping is a pivotal strategy for achieving Sustainable Development Goal (SDG) number 2—*End hunger, achieve food security and improved nutrition and promote sustainable agriculture* (SDG 2)—by enhancing food security agroecosystem resilience and sustainability. By integrating diverse species within the same plot, this sustainable approach takes advantage of the beneficial interactions between them. The simultaneous cultivation of multiple crop species within the same field increases agricultural diversification and contributes to a more resilient production system, breaking the uniformity of modern intensive agriculture. The objective of this review is to evaluate intercropping practices throughout the Mediterranean, specifically in Southern Europe (Portugal, Spain, Italy, and Greece), North Africa (Morocco, Algeria, and Tunisia), and the Middle East (Turkey, Israel, and Jordan). This review intends to show advantages and disadvantages of intercropping and crops used and also highlight how intercropping systems affect crop production and quality, soil quality and microbiome, and proliferation of weeds, pests and diseases. The literature suggests that diversification in agriculture supports biodiversity and ecosystem services by the cultivation of diverse crop species together and, hence, may reduce independence in external outputs such as nutrient supply, pesticides and soil amendment. Despite the potential benefits of intercropping, the major caveats of this practice are the competition between different crops on resources, potential risks of plant protection, technical challenges of integrating the different requirements of each crop used in the system, and culture-related restrictions or regulations.

Keywords: productivity; crop production; soil quality; economic analysis

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1. Introduction

Supported by the advantages of the second green revolution [1], food production went through massive intensification of farming and utilization of monocultures to achieve food production for a growing demand. This uniformity in modern farming systems [2] is exposing crops to pest outbreaks and damage derived by climatic conditions. Intensive and uniform agriculture produces significant environmental impacts, such as a decrease in biodiversity, available water scarcity, and soil degradation [3–6]. Due to these negative effects of intensive monocultures, specialists and practitioners are advocating for changes in the current agricultural systems to promote an increase in sustainability and avoid irremediable environmental impacts [3,7]. The governmental policy to change these paradigms is quite evident in the 2030 Agenda for Sustainable Development,adopted by all United Nations member states, especially in the Sustainable Development Goal (SDG) number 2—*End hunger, achieve food security and improved nutrition and promote sustainable agriculture* [8]. Considering that crop plant diversity is positively correlated to soil biodiversity [9] and its functioning [10], the practice of intercropping can simultaneously promote food security and protect the environment in industrialized and large-scale agriculture scenarios [11,12].

Intercropping is one of the pillars of sustainable agriculture and has been practiced in several modifications due to the need to mitigate the environmental stress caused by conventional methods [13]. It is considered a sustainable strategy that includes the cultivation of diverse crop species together in the same area to take advantage of the beneficial interactions between them [14]. Intercropping is considered modest in demand of inputs for nutrient supply, plant protection and soil conservation. Evidence suggests that intercropping helps to decrease the incidence of pests, disease and weeds and increase the soil fertility and, consequently, the yield [15,16]. In addition to being an alternative source of income compared with monocrops, intercropping allows for a wider root distribution of species along the field profile, facilitating niche discrimination of the different crop roots and their activity [13].

Intercropping can be divided into four types of field designs [17]: (a) mixed intercropping (two or more crops growing on a plot, co-existing with each other without distinct arrangement); (b) relay intercropping (cultivation of crops on the same field but with overlapping time of development and harvest); (c) strip intercropping (planting crops in parallel strips, allowing crop interactions and independent cultivation); and (d) alley cropping (crops planted in a single or double row, allowing for interspecific interactions). A complete description of the different intercropping systems has been made by Moreira et al. [18]. Intercropping is a common system used in countries with high amounts of subsistence agriculture and low amounts of mechanization. However, despite the benefits of intercropping, this practice is rarely adopted in large-scale, intensive monocrop farming. Therefore, for upscaling intercropping to wider use, intercropping systems must be optimized to enhance resource-use efficiency and crop yield, and the wider benefits must be promoted, including the delivery of multiple ecosystem services in addition to the provisional services [17].

1.1. Advantages and Disadvantages of Intercropping

Intercropping generates dynamic alterations in the soil due to increased plant material in the rhizosphere, which can improve plant–soil–microorganism interactions and confer a series of benefits for plants and improvement in the soil structure [19]. As for water penetration and retention in the soil, evidence shows that adding vegetative cover, such as in orchard intercropping, mitigates surface runoff by increasing macrospores in the soil profile [20]. According to Chamkhi et al. [21], intercropping legumes affect soil microbiology, thereby directly impacting beneficial soil populations. Their study states that the use of legumes in intercrops supports biological balance and contributes to indirect control of pest nematodes. Intercropping also promotes the development of diverse root types, alters overall root distribution and architecture, and influences exudation processes within the rhizosphere [20]. In addition to the benefits for the soil, the implementation of an annual crop associated with orchards contributes to the multiplication of beneficial insects and the attraction of pollinators, which is a very specific need for many fruit species that are self-incompatible [22]. A study conducted in Australia by Saunders et al. [23] investigated the relationship between wild pollinators and live ground cover in orchards. According to the authors, the soil cover could interact with the other elements of the orchard so that pollinator communities could maintain themselves in the long term. In the case of perennial crops, such as almond (*Prunus amygdalus* B.) orchards, associated with annual crops, alley cropping is not a common practice due to competition between plants [24]; when soil cover is greater than 45% from the total canopy cover of trees, the competition potential increases significantly. The benefits of intercropping will differ according to its agronomic objective and the crop used, whether for reasons of soil enrichment, crop diversification, or landscape aspects [25]. It is worth noting that the intercrop residue cannot interfere with the management and harvesting operations of the perennial crop.

According to Abourayya et al. [13], the intercropping of snap bean (*Phaseolus vulgaris* L.) with almonds had a positive influence on the growth parameters and yield of the leguminous crop. In their study, the authors verified that the growth characteristics and the constituents of the leaves of young almond trees were superior when the almond tree was intercropped with the snap bean in comparison to the almond trees cultivated as a monoculture. In addition, an increase in pH and organic carbon content as well as N, P, exchangeable K, Ca, and Mg was observed when the residues of snap bean pods were incorporated into the soil [13]. In semi-arid regions, cereals cultivated between rows of fruit trees achieved a positive land-use efficiency. However, it is important to establish adequate spacing between the crops to ensure there is no photosynthetic limitation of the mutual crops or competition for resources between trees and other species [26]. A further positive effect of intercropping is the increase in the storage of carbon and nutrients in the agrosystem's soil [26]. Along with the potential benefits of an intercropping system of trees with other crops, it is important to integrate other farming practices such as tillage strategies that assure the long-term stability of agroecosystems, with an emphasis on preserving and improving soil health [27].

Despite the potential benefits of intercropping over monocropping, some disadvantages could impact negatively on the agricultural system. Inter-species competition for limited resources may lead to yield loss, management of extra moisture in the crop canopy may result in pest and disease outbreak, and there may be expression of allelopathic effects and difficulty in agrotechnical management of different mechanical tools [16]. Furthermore, intercropping may adversely affect the efficiency of farm mechanization. Logistical complications arise particularly when the component crops exhibit divergent requirements for fertilization, irrigation, and phytosanitary protection [16,18].

1.2. Crops Used in Intercropping

Legumes and annual cereals are more commonly used for intercropping [28]. In this sense, the use of leguminous species has been disseminated, considering their productive potential and high efficiency in the use of light, water, and nutrients. In addition, its relationship with mycorrhizae favors the development of other species and improves rhizosphere conditions, especially when associated with perennial crops such as fruit trees [21]. This association upgrades N and other mineral nutrient assimilation, improving yield production and quality [28]. Intercrops include barley, oats, sorghum, peas, lentils, clover, legumes, brassicas, sunflowers or service crop mixtures [29]. A review by Moreira et al. [18]

shows that more usual crop species or mixtures are used in the intercropping system. The major use of cover crops is to maximize the use of resources in a range of environmental conditions [29]. Therefore, cover crops are more often called service crops. However, the success of intercropping will depend on how the dynamics of the resources available within the system, available to both cultures, can perform positive interactions with each other [21]. This review intends to explore the use of an intercropping system in different regions of the Mediterranean basin: South Europe (Portugal, Spain, Italy, Greece), North Africa (Morocco, Algeria, Tunisia) and the Middle East (Turkey, Israel, Jordan). This review highlights how intercropping systems affect crop production and quality, soil quality, microbiome, and weeds, pests and control regarding monocropping systems and also intends to show, in an economic way, the effect of the intercropping.

2. Methodology

Using databases such as ScienceDirect, MDPI, ResearchGate, Springer Nature, Taylor and Francis, etc., a search was conducted to obtain relevant research articles about the effect of intercropping in Mediterranean agriculture. Keywords including intercropping, mediterranean crops, crop quality and production, soil quality and microbiome, effect of intercropping in weeds, pests and control diseases, and economic analysis of intercropping application were used. Inclusion factors were peer-reviewed published research of open-field studies and research conducted in the Mediterranean region (Iberian Peninsula, South Europe, Middle East and North Africa) in major crops such as almond trees, vines, olive trees and pomegranate trees. Exclusion factors included greenhouse trials, work that was not published in the English language and studies published prior to the year 2000.

3. Intercropping in the Mediterranean Region

The Mediterranean region is characterized by long dry, hot periods and wet, colder winters. In the last decades, this area has faced several changes including climate change, depleting water resources and rapid urban extension [30]. Consequently, in the implementation of Mediterranean intercropping systems, it is important to avoid the utilization of crops that could compete for water with the other crops [31]. Moreira et al. [18] identified several studies of intercropping in almonds along the Mediterranean region. Ideally, a well-designed intercrop system supports biodiversity and its functioning, manages pests and weeds, enhances crop productivity and quality, and improves soil fertility in the agricultural ecosystem [32]. Table 1 presents several studies on intercropping systems across the Mediterranean region (Iberian Peninsula, South Europe, Middle East and North Africa). These studies illustrate that intercropping is still perceived as “adding another crop between tree lines” rather than studying the optimal design of the field with more than a single crop.

Table 1. Intercropping systems in several locations of the Mediterranean region.

Region	Intercropping		Effects
Iberian Peninsula	Almond orchard	Faba bean Vetch Pea	Legumes increased the antioxidant activity and total polyphenol content of grapes; [27]
		Caper Winter thyme	Intercropping increased the moisture content and organic carbon of the soil in comparison to monocultures; Reduction in CO_2 emission from the soil; [33]
	Olive orchard	Saffron Vetch Oat Lavander	Intercropping increased soil organic carbon compared to the separated monocultures; [31]
		Leguminous	Leguminous service crops increase the photosynthetic activity of olive trees; also increase tree nutritional status, olive yield and moisture and size of olives; [34,35]
		Self-reseeding annual legume species	Self-reseeding annual legume species increase the cumulative yield of olives; increase the microbial diversity and enzymatic activities in the soil; [36]
		Mixture of early-maturing and self-reseeding annual legumes	Legumes are less effective in increasing organic C than non-legume species; [37]
South Europe	Vine	Self-reseeding annual legume species	Self-reseeding annual legume species increase the N concentration and content in leaves, clusters, and canes of vines; [38]
		Natural covering Legume mixture Grass mixture Conventional soil tillage	Service crops reduce grape production; Grass mixture increased sugar, anthocyanins and polyphenols; Legume mixture and natural covering reduced total polyphenols and anthocyanin content of the grapes; [39]
		Sage	Influence volatile compounds in grape berries (decrease phenols, increase terpenes, alcohols, C6 derivatives); [40]
		Subterranean trefoil Yellow serradella Burclover Biserrula Ryegrass Dallisgrass	Service crops reduced the grapevine vigor; Service crops did not affect yield; *Dactylis glomerata* L. affected positively the amount of total anthocyanins; [41]

Table 1. *Cont.*

Region	Intercropping		Effects
South Europe	Olive orchard	Barley Vetch	Increase N fixation and improved olive production per tree; [42]
		Asparagus	Increase global productivity and biodiversity of olive groves; [43]
Middle East	Almond orchard	Bean	Significant impact on the nutrient composition (N, P, K) of almond leaves; Increase in total chlorophyll content; [13]
		Barley Wheat	Increase soil organic carbon, total N, P and K; [26]
	Pomegranate orchard	Basil Rosemary	Increase in growth parameters, leaf minerals and chlorophyll, fruit quality (total soluble solids, total acidity percentage and anthocyanin content); [44]
	Vine	Garlic	Decrease population of phytonematodes acting as biocontrol; [45]
		Fenugreek Fennel Cumin Parsley	Increased N, P, K and organic matter in the soil; Increase nutritional status, vegetative growth, yield and berry quality; [46]
North Africa	Olive orchard	Faba bean Wheat Coriander	Faba beans improve olive production; Wheat affects negatively growth and production; [47]
		Faba bean Lentil Durum wheat Bread wheat Barley	Leguminous improves soil N availability, improving the soil fertility due to the fixation of atmospheric N; [48]
		Barley Vetch	Service crops increased soil organic carbon; [49]
		Oat Bread wheat Fenugreek Vetch	Increase soil organic matter and macronutrient levels; *Trigonella foenum-graecum* increase soil N; [50]

This table summarizes Mediterranean studies (Column 1) focused on intercropping within the region's primary crops (Column 2). Columns 3 and 4 detail the specific crop combinations used, and the outcomes observed in each study.

3.1. Productivity/Yield

The intercropping system is a viable strategy to improve crop productivity/yield due to several mechanisms, such as increased nutrient use efficiency and optimized spatial arrangements, beneficial modulation of microclimatic conditions, and synergistic effects of mutual plant protection [14,51]. The increase in yield is explained by the improvement in capturing and converting resources such as light radiation, water, and nutrients into biomass by the crops used in intercropping than if they were grown separately [51]. A study developed by Razouk and collaborators [47], in a rainfed olive (*Olea europaea*) orchard in Morocco, verified the improvement of olive production with the utilization of faba beans when compared with the application of wheat and coriander. They verified that wheat reduced the growth and yield of olive trees. This study indicated that legumes are less competitive than cereals for soil resources, especially when saplings are established. In this case, the use of wheat as intercropping reduces the vegetative growth of olives because of the competition for water and nutrients. In Morocco, the critical olive shoot growth occurs in June, which overlaps with the final filling and maturation of wheat. The use of faba bean does not compete with the olive growth season because its growth cycle is during the olive dormancy and it is harvested at the end of April. Furthermore, the use of faba bean increases olive growth and leaf area by 22–30% due to the enrichment of soil by nitrogen biologically fixed by this legume [47]. The use of legumes as intercropping results in a biological nitrogen fixation between 100 and 300 kg N/ha^{-1} from the atmosphere [21].

In Portugal, Martins et al. [34] verified an increase in olive yield of 34% from 2017 to 2019 in olives intercropped with leguminous crops. The yield benefits stem from the offset phenology of the legume species relative to the olive trees. Early senescence, coupled with spring rainfall, facilitates the timely decomposition of residues and subsequent nutrient uptake by the trees. Also, the mulch obtained by plant residues contributes to reducing soil temperature and increasing water availability, the limiting factor for yield in Mediterranean agroecosystems [34]. Likewise, Correia et al. [36] observed an increase of 37, 53 and 95% higher cumulative yield over 4 years with the sowing of self-reseeding annual legume species. The higher yield obtained in these olives trees could be associated with better physiological performance during the summer (better water status and net photosynthetic rate). Rodrigues et al. [37] also observed an increase in cumulative olive yields (85.1 kg/tree) in the five harvest years. The increase in yield has been associated with the better N nutritional status observed in olive trees intercropped with legumes.

Paoletti et al. [43] grew wild asparagus in a super high-density and a high-density olive orchard in Italy. They verified an increase in total productivity of asparagus in both systems in comparison to the control monoculture. Although the effect of asparagus intercropping on the olive yield was not quantified in their study, the present results suggest that this agroforestry system is advantageous in terms of greater productivity per unit of land area, in particular by obtaining additional crop production in the olive orchard, compatible with olive orchard management. The most common tool to evaluate the overall production of agroforestry intercropping versus monocultures is calculating a land equivalent ratio (LER) higher than 1 [52,53]. To evaluate the LER of a system, it is necessary to quantify the yield produced in each of the monocultures (in the last example, olive monoculture and asparagus monoculture) and the yield of each crop within the intercropping design. Likewise, intercropping systems affect positively the productivity of vines. Belal et al. [46] intercropped Thompson seedless vines with fenugreek (*Trigonella foenumgraecum*), anise (*Pimpinella anisum*), black cumin (*Nigella sativa*), and parsley (*Petroselinum sativum*) and observed an increase in yield per vine, soluble solid content and total sugar and a reduction in the total acidity of the grapes with fenugreek intercropping. This was verified with the utilization of leguminous. The positive effect of the utilization of medicinal plants, especially fenugreek, as intercropping is related to the ability of these plants to fix atmospheric nitrogen in the soil, improving the nutritional status of the major crop. Also, the residual organic parts of the fenugreek improve the physical and chemical properties of the soil and the microbial activity, improving root growth and nutritional status of the vine, which increase shoot length and leaf area, enhance berry weight and cluster weight, and result in a higher final yield [46]. In contradiction to this insight, Muscas et al. [39] observed a reduction in the grape production due to the modification of yield components by the utilization of service crops such as a legume mixture and grass mixture.

Although there is an increase in productivity observed in intercropping systems, the development of new types of mechanization is essential for large-scale application of intercropping. Nowadays, some farmers consider intercropping practices to be more labor-intensive than monocultures [54], and farm machinery can be adjusted in strip intercropping [16]. Also, intercropping could challenge the practical management of some operations such as weed management between the crop line, herbicide incompatibilities, and increased complexity of sowing and harvest [55].

3.2. Crop Quality

Several studies demonstrated the positive effect of intercropping on crop quality (Table 1). A study performed in Spain, by Cárceles Rodríguez et al. [27], showed an increase in the nutritional value of almonds by increasing antioxidant activity and total polyphenol content when intercropped with faba bean, vetch and pea. In vineyards, the utilization of service crops, such as a legume mixture and grass mixture, changed the grape must quality. However, the utilization of a legume mixture and spontaneous vegetation in a vineyard showed a negative impact on the total polyphenols and anthocyanin content [39]. In another study in vineyards, Belal et al. [46] reported an increase in grape quality. The authors verified an increase in soluble solids content and total sugar and a reduction in total acidity in berries from vines intercropped with fenugreek. Rodríguez-Declet et al. [40] tested the influence of sage in vines and observed a decrease in phenols and an increase in terpenes, alcohols, and C6 derivatives when the volatile compounds of grapes were evaluated. Aromatic plants showed a positive effect on pomegranate quality and quantity. Abdelfatah et al. [44] verified a decrease in fruit cracking and an increase in total soluble sugars, total acidity and anthocyanin content in pomegranate intercropped with basil and rosemary. An amount of anthocyanin has also been observed in vines intercropped with perennial grass such as dallisgrass [41].

The positive effect of intercropping on quality, mentioned in several studies above, is related to the improvement of soil quality. The use of crops such as legumes or aromatic plants increases the physical (bulk density, available water content, and aggregate stability) [27], chemical (pH, electrical conductivity, soil organic content, N, P, K, and micronutrients), and biological (greater microbial activity) [27,34,46] properties of the soil. These parameters affected positively the increase in the yield and quality (physical and chemical) of the major crops introduced in the system [27,46].

The increase in the crop yield in intercropping systems could be improved by informing the design of the intercropped field, taking into account aspects such as stand density, crop identity, seed rotation, and tree pruning: for instance, adjust adequate spacing between crops to prevent shading or maximize border rows to enhance light capture when only one crop is present in the field [32]. Crop selection has an important role in designing a more optimal intercropping system. For instance, soybean and eggplant could be used in low-density plantations due to the low tolerance to shade, and chickpea is suitable for long dry season and low water availability situations [56].

3.3. Soil Quality

The intensification of agriculture in the last century has allowed an increase in crop yields. However, the introduction of fertilizers, pesticides and intense mechanization has led to an increase in greenhouse gas (GHG), a decrease in soil organic matter [33] and a reduction in soil biodiversity [57] that will decrease agricultural sustainability [58]. Some studies demonstrated the good effect of intercropping application on improving soil quality. Especially, the use of cereal and legumes seems to enhance symbiotic N fixation, improving crop growth through the action of soil microorganisms [14]. Cárceles Rodríguez et al. [27] studied the effect of the intercropping of faba bean, vetch and pea in almond orchards. In their study, performed in Spain, the authors verified an improvement in the physical properties of the soil, soil organic carbon content, N, K, and micronutrients and an increase in microbial activity. Another global meta-analysis, encompassing 49 studies, found that cover cropping—particularly with grasses, brassicas, and legumes—significantly altered soil carbon fractions. Compared to bare or fallow soils, cover-cropped systems showed a richer biodiversity [9], an average increase of 14.94% in particulate organic carbon (POC), especially within the top 0–10 cm of soil, and a more gradual but consistent increase of 5.56% in mineral-associated organic carbon (MAOC), highlighting both rapid and sustained pathways of carbon sequestration [59]. Sánchez-Navarro et al. [33] showed an increase in the moisture content and organic carbon of the soil in almond intercropped with thyme compared to a monoculture and a significant reduction in CO_2 emission with intercropped caper and thyme.

Olive orchards are also an important Mediterranean crop where intercropping is commonly practiced. Aguilera-Huertas et al. [31] intercropped olive trees with saffron, vetch, oat and lavender. They observed an increase in carbon in the soil in all the intercropping systems used in comparison to conventional tillage. In Portugal, Martins et al. [34] reported an improvement in the soil moisture with the application of legumes as service crops in olive orchards. Indeed, olive trees grown under the influence of cover crops seem to have a better plant water status due to lower stomatal resistance. Akchaya et al. [60] suggested that agronomic practices such as intercropping improve ecosystem services, increasing water infiltration and improving soil water availability by facilitating water movement and ensuring optimal moisture distribution in the soil. The studies of Mazzafera et al. [56] and Hatfield and Dold et al. [61] also indicated an increase in water-use efficiency when intercropping was implemented regarding monocropping. Toker et al. [14] defends that intercropping systems have the ability to upregulate important genes that allow an improvement in the response under drought deficiency. However, to realize the benefits of intercropping, it is important to carefully choose the crops to use [31]. The different root structures (shallow roots and deep roots) allow the plants to access various soil layers for nutrients and water, competing with other plants [60,62]. For instance, the use of leguminous was more competitive for water than fescue or weeds, impacting the trees' growth. However, in the long term, the improved nitrogen status of the trees compensated for the initial water competition [63]. The use of pulses such as chickpeas and lentils has a lower water demand and demonstrates a higher water use efficiency (WUE) compared to the use of cereals and oilseeds. Also, deeprooted legumes like lucerne and clovers effectively mitigate waterlogging by extracting moisture from the deeper soil layer [60]. The deep roots observed in legumes allow a better redistribution of the water from deeper soil layers to drier topsoil at night, ensuring the resource efficiency of the utilization of legumes as intercropping [60].

Rodrigues et al. [37] observed an improvement in soil fertility with the use of legume service crops. These authors verified an increase in the availability of N (84.4 mg/pot) in soil sampled at 0–10 cm at 4 years after the establishment of the ground-cover treatments. Also, an increase in the soil biological activity has been verified in the plots with leguminous. The authors verified an increase in soil bacteria and fungi population in plots with leguminous (7.20 log cfu g^{-1} and 5.30 log cfu g^{-1}, respectively) when compared with natural vegetation unfertilized plots (6.74 log cfu g^{-1} and 4.77 log cfu g^{-1}). The increase in microbial soil could be related to the faster decomposition of the leguminous residues that have more N than lignin [37]. Sulas et al. [38] introduced self-reseeding annual legume species intercropped with vineyards. They verified an increase in N concentration content in vine organs, mainly in leaves, clusters, and canes (+25% of total N). Also, Mantzanas et al. [42] verified an increase in N with the utilization of barley mix with vetch intercropped with olive trees. In their study, an increase in barley yield production as well as in olive tree production was likewise observed in comparison to their yield in a monoculture. The increase in N in both studies was associated with the utilization of legumes [38,42] that have the capacity to fix atmospheric N by the action of the rhizobium [21]. Also, the incorporation of leguminous residues in the soil, once mineralized, can increase soil nitrate and ammonium contents, increase the soil quality and also represent an important N contribution for improving production [38,42].

In Iran, Abbasi Surki et al. [26] studied wheat and barley intercropping with almond trees in comparison with the conventional sole-cropping. They verified an increase in soil organic carbon and total N, P and K in soil with barley–almond tree intercropping. However, competition for light has been observed, affecting negatively the cereals. This parameter could be optimized by adjusting tree line orientation and by pruning the almond trees to remove some branches, opening the way for light intensity. It is also important to note that the study was conducted in a semi-arid region with a bimodal rain pattern, which is not typical of the Mediterranean climate. In a study of pomegranate trees, the authors verified an increase in growth parameters, leaf minerals and chlorophyll when intercropped with basil and rosemary [13,44]. Abourayya et al. [13] observed a significant impact on the nutrient composition of almond leaves, particularly in terms of N, P and K percentages, by intercropping almond trees and snap bean in the Nubaria region, Egypt. In another study, Belal et al. [46] verified an increase in N, P, K and organic matter in the soil and an increase in nutritional status and vegetative growth of vineyards intercropped with fenugreek. Also, the utilization of leguminous increases soil N availability, improving the soil fertility due to the fixation of atmospheric N [48]. The increase in soil quality in terms of soil organic matter and macronutrient levels has also been verified by Guesmi et al. [49] and Elhaddad et al. [50] in olive trees intercropped with barley and vetch and oat, bread wheat, fenugreek and vetch, respectively.

Intercropping with alfalfa induced a significant increase in shoot and root biomass of grapevine in the agricultural soil [64]. Furthermore, in the Cd/Pb-contaminated soils planted with grapevine, a slight increase in root biomass was observed by Jeder et al. [64]. De Conti et al. [65] demonstrate that intercropping may be a strategy for phytoremediation of vineyard soils with high copper (Cu) content. When grapevine was grown in three cropping treatments, monocropping, intercropping with brownseed paspalum (*Paspalum plicatulum*) and intercropping with carpetgrass (*Axonopus affinis*), intercropping young grapevines with brownseed and carpetgrass was efficient in promoting the growth of young grapevines at moderate and low levels of Cu contamination by reducing Cu bioavailability.

Sometimes, some nutrients such as P are available in the soil but not accessible to plants. The interaction between the root exudates of some species modifies the rhizosphere conditions, enhancing the availability of nutrients present in the soil [14]. By enhancing soil organic matter, fostering microbial diversity, and optimizing nutrient availability, intercropping serves as a cornerstone for sustainable agricultural development. Integrating diverse cropping patterns into modern agricultural practices not only promotes ecological equilibrium but also establishes the foundation for more productive and resilient cropping systems [14].

3.4. Soil Microbiome

Intercropping exerts a profound influence on soil microbiome dynamics, primarily driven by the secretion of root exudates and the substantial transfer of carbon (C) and (N) to the rhizosphere, which augments both microbial abundance and taxonomic variety [14]. In nutrient-limited environments, soil microbial communities play an important role in improving plant growth by facilitating nutrient mineralization and competitive acquisition [66]. Generally, intercropping systems enhance soil enzymatic activity and elevate microbial biomass indices, which correlate significantly with increased taxonomic diversity and the stability of microbial co-occurrence networks [19]. By diversifying the host plant environment, these systems orchestrate microbially mediated metabolic pathways that support optimized nutrient uptake and sustainable productivity [67]. Furthermore, under drought conditions, positive shifts in root–soil–microbiota interactions have been observed, leading to improved soil health and enhanced microbial host fitness [68]. Despite these benefits, a comprehensive understanding of the mechanisms through which intercropping and microbial communities directly influence crop yield is still lacking [69]. Certain intercropping configurations may even negatively alter the rhizosphere microenvironment—modifying factors such as soil temperature, moisture, and mineral availability—thereby creating unfavorable conditions for specific microbial taxa [70]. Consequently, the relationship between intercropping and microbial diversity warrants further investigation. Most current research focuses on the immediate impacts of agricultural management on biodiversity rather than exploring the evolution of microbial life strategies throughout the duration of the intercropping cycle [71].

Recent work by Li [72] pursued the underlying ecological relationships between the microbiome and its environment, reporting a 68.7% increase in microbial diversity within intercropping systems compared to monocultures. Their study also noted enhanced complexity and stability across both bacterial and eukaryotic communities. They also observed that soil properties, such as total phosphorus, available phosphorus, pH, and easily oxidizable carbon, have a positive correlation with the bacterial community, and oxidizable carbon was the main factor influencing the soil eukaryotic community.

Similarly, metagenomic analyses by Shu et al. [73] revealed a significant rise in microbial diversity (both bacterial and fungal communities), particularly in microorganisms related to the soil nitrogen cycle. In situations of soybean intercropping, they observed a stronger influence on the functional genes associated with soil nitrogen cycling due to an increase in microbiome functional adaptation. This increase in microbial diversity could be linked to the production of heterogeneous belowground root exudates [74] and aboveground volatile organic compounds triggered by interspecific plant interactions [75]. These diverse plant-derived metabolites optimize resource availability for neighboring vegetation and modulate rhizosphere dynamics. These processes are facilitated by a tripartite network of host-to-microbiome, inter-microbial, and microbiome-to-host interactions [76].

Studies by Zhang et al. [77] showed an increase in the bacterial community diversity with intercropped maize and soybean in contrast to monocultures. They verified enrichment in microorganisms such as *Gemmatimonas* and *Bradyrhizobium* that are responsible for the increase in the soil nitrogen content. *Gemmatimonas* is responsible for reducing the N_2O to nitrate in soil, whereas *Bradyrhizobium* is able to form a nitrogen-fixing symbiosis with *Rhizobium* in soybean's root system, increasing the soil nitrogen content.

Research by Zheng et al. [78] indicates that intercropping fosters a healthier soil microbiome by boosting beneficial bacteria such as *Proteobacteria*, *Actinobacteriota*, *Gemmatimonadota*, *Gemmatimonas*, *Conexibacter*, and *Sphingomonas* while suppressing pathogens like *Fusarium*. Compared to monocultures, intercropping reduced *Fusarium* impact by approximately 28–37% in early stages and maintained significant suppression through the peak and late stages of the disease cycle. Moving forward, future studies should focus on the underlying interactions between soil, microbes, and plants. Also, further characterization is needed of the interaction between intercropping-driven environmental and microbial community assembly, which remains a significant challenge, particularly under the unique constraints of arid and semi-arid soil systems [71].

3.5. Intercropping Impact on Weeds, Pests and Diseases

Intercropping is an important strategy for weeds and the control of pests in comparison to monocultures due to the increase in biodiversity and the reduction in the utilization of herbicides and pesticides [14,28]. In this sense, Mohsen et al. [45] observed a decrease in phytonematode population with the intercropping system vineyard–garlic. Muscas et al. [39] also observed a decrease in the pest mealybug population (reduction in survival, fecundity and fertility) in vineyards intercropped with a grass mixture. Hahn and Cammarano [79] performed a meta-analysis of 272 estimates of insect herbivory on crops. Their analysis showed that intercropping exhibited reduced herbivory when compared to monocultures. The authors concluded that diversification of agrosystems by mixed planting can contribute significantly to pest control and, overall, support both food security and ecosystem services. More recent global analyses reinforce these findings. A 2023 meta-analysis by da Silva et al. [80] found that intercropping increased the abundance of natural enemies by 36% and species richness by 27% while simultaneously reducing pest abundance and density by 38% and 41%, respectively. These benefits were especially pronounced in systems combining cereals and legumes or employing strip-row designs. The mechanisms behind these effects include improved habitat for beneficial arthropods, disruption of pest host-finding behavior, and reduced resource concentration, all of which contribute to the suppression of pest populations without the need for chemical inputs.

Weed suppression is one of the most consistent and well-documented benefits of cover cropping. Leguminous and grass species, such as underground clover and hairy vetch, are widely used in Mediterranean orchards—including apricot, olive, and citrus—to reduce both annual weed emergence and the persistence of the soil weed seedbank. In a multi-year study in Sicilian apricot orchards, subterranean clover reduced surface weed biomass by up to 86% and decreased the seedbank by over 50% compared to conventional monocrop management [81]. Similarly, in Turkish apricot orchards, sowing mixtures of pannonian vetch (*Hungarian vetch*), wheat (*Triticale*), phacelia (*Phacelia*), and buckwheat achieved more effective suppression of weed species richness and density than either herbicide applications or mechanical control [81]. More recently, Cechin et al. [82] demonstrated that integrating cereal rye, common vetch, black oat and feral radish as a winter service crop resulted in an 80–96% decrease in emergent weed density and modest reductions in the weed seedbank after three years of continuous management.

Soilborne diseases are considered a major limitation to crop production. Soilborne plant pathogens, such as *Rhizoctonia* spp., *Fusarium* spp., *Verticillium* spp., *Sclerotinia* spp., *Pythium* spp., and *Phytophthora* spp., can cause 50–75% yield loss for many crops such as wheat, cotton, maize, vegetables, fruit and ornamentals, as reported to date [83]. Compared to pepper monoculture, a large-scale intercropping study of maize grown between pepper rows reduced disease levels of the soilborne pepper *Phytophthora capsici* blight. Maize could form a “root wall” to restrict the spread of *P. capsici* across rows in maize and pepper intercropping systems. Antimicrobe compounds secreted by maize root were one of the factors that resulted in the inhibition of *P. capsica* [84]. Intercropping of peanut with the Chinese medicinal herb cang zhu (*Atractylodes lancea*) effectively suppresses soilborne *Fusarium* populations, a common peanut disease, by means of volatiles from the rhizome, resulting in increased peanut yields [85]. An herbaceous mixture composed of chrysanths (*Chrysanthemum* spp.) (3%), coriander (*Coriandrum sativus* L.) (10%), garden rocket (*Eruca vesicaria* L.) Cav. (5%), yellow sweet clover (*Melilotus officinalis* L. Pall.) (8%), sainfoin (*Onobrychis viciaefolia* Scop.) (22%), meadow sage (*Salvia pratensis* L.) (10%), arrowleaf clover (*Trifolium vesiculosum* Savi.) (4%) and common vetch (*Vicia sativa* L.) (30%) was applied as the interrow service crops. Compared with conventional soil, the soil treated with service crops displayed increased suppressiveness against the olive soilborne pathogen *Verticillium dahliae* [86].

3.6. Economic Analysis

Intercropping supports soil health, biodiversity, and ecosystem services [18,87], which are increasingly valued by society. Social demand for sustainable practices [88] can translate into non-market benefits valued as highly as direct crop revenues, with strong public support for diversification [89]. These systems also help mitigate environmental risks associated with intensive monocultures. The extensive literature on intercropping often focuses on the effects observed above, primarily related to the sustainability of Mediterranean agricultural systems [90] and, more broadly, to the reduction in the environmental footprint [91].

However, studying the economic effects of intercropping highlights several points for analysis that may be particularly important for farmers, who bear the business risk and greater management complexity [92–94].

Mediterranean intercropping systems offer significant economic and environmental opportunities, especially when tailored to local conditions and markets [94–96]. Some authors primarily analyze the effects of intercropping in terms of yield increases compared to monoculture [15,97] or evaluate productivity using the land equivalent ratio (LER) parameter on equal cultivated land [98]. However, efficiency measured solely in yield terms (as the standard LER does) is not sufficient to assess economic profitability [99]. In fact, Dowling et al. [55] noted that an LER greater than one indicates only a yield advantage of the intercrop, not necessarily a profit advantage; similarly, Martin-Guay et al. [100] highlight that “LER does not take into account whether one of the crops is more valuable than the other”. The LER does not account for differences in the economic value of the component crops.

Other studies evaluate the effects of intercropping on gross income, although this result depends significantly on the management practices adopted or on external factors, such as agroecological ones [101]. It has been demonstrated that proper crop complementarity—‘for radiation, water, and land in time and space’—maximizes the profit of intercropping compared to monoculture [102].

Several studies have assessed the gross benefit, NPV (net present value), and BCR (benefit–cost ratio) of intercropping compared to monoculture, recording positive values for these indicators [103] or gross margin [104]. In summary, intercropping systems can be economically advantageous; however, current metrics require improvement to account for differences in production costs, value ratios, and risk preferences [105].

3.6.1. Economic Benefits and Profitability

Intercropping can increase land use efficiency and provide higher or more stable incomes compared to monoculture [106], especially in low-input scenarios [98,107,108].

Specifically, Martin-Guay et al. [100] demonstrate that intercropping can increase gross energy and income by 38% and 33%, respectively, while using 22% less land, making it a promising sustainable intensification strategy for agriculture. Studies on intercropping systems, such as oilseed–legume [96] and olive–wild asparagus [94], indicate potential improvements in gross margins, LER ratios (LER > 1), and economic resilience compared to sole cropping, while in the case of triticale–lupin, a recent study [107] provides evidence of higher agronomic performance, improved LER (LER > 1), and enhanced N yield relative to monocultures. The choice of crop combinations and local market conditions is critical for maximizing profitability [95,99,106], while market access, consumer preferences, and value chain integration are critical for realizing the economic potential of intercropping [18,88].

3.6.2. Negative Factors on Yields and Profitability

Despite its advantages, intercropping presents challenges such as increased labor requirements, management complexity, and difficulties with mechanization [99,105]. Indeed, profitability depends on higher initial costs or workloads (annually increasing by 75%), particularly for labor-intensive crops (e.g., wild asparagus within olive orchards) [94]. The practical management of essential agronomic operations with mechanization is difficult in situations of crops with dissimilar requirements for fertilizers, water and plant protection. Also, during harvest of the early maturing crop, there may be some mechanical disturbance to the long-duration crop. Also, during the harvest, a mix of grains could occur, which will incur additional cost for the separation [16]. So, it is important to build farm machinery that can be adjusted for strip intercropping [16]. For example, one of the objectives of the Leguminose project (Horizon Europe) is to develop new machinery that can separate mixtures of different seeds from each intercropped crop [109]. Also, intercropping could challenge the practical management of some operations, such as weed management between the crop line, herbicide incompatibilities, and increased complexity of sowing and harvest [55]. The use of herbicides is difficult, as most of the herbicides are crop-specific and the emergence of weeds and crops occurs simultaneously [16]. Although intercropping covers a great portion of land, which results in fewer weeds [16], in some cases, the crops used do not suppress weeds efficiently [110]. Nurk and collaborators [110] tested the effect of mixtures of maize and climbing beans as an alternative to monocrop maize under different site and management conditions. They observed that mixtures were not efficient in suppressing weeds, and in some cases, the mixtures' yield clearly declined with increasing weed coverage.

In dry, warm regions, yield benefits may also be limited by water constraints, resulting in potential yield losses of several percentage points, depending on the crop, in areas where adaptation measures are not implemented [111]. The management of N fertilization is also a very sensitive factor and, therefore, complex to regulate. Indeed, a suboptimal dose of N fertilization can cause production results to deviate from those desired by the farmer (e.g., greater production of fodder rather than grain) [112].

3.6.3. Policy and Market Context

Policy frameworks, such as the European Green Deal and the Common Agricultural Policy (CAP), increasingly support diversification and sustainable practices [89]. However, their implementation varies across regions and farm structures [95]. Moreover, Morugán-Coronado et al. [108] highlight how farmer perceptions, local environmental constraints, and knowledge gaps can hinder the adoption of sustainability-oriented practices. In contrast, market access, consumer preferences, and value chain integration are critical for realizing the economic potential of intercropping [18,88]. Overall, policy support and consumer demand for sustainable products are growing; however, scaling up adoption requires stronger value chain integration and more targeted incentives [88,89,113].

The results from European projects such as LEGUMINOSE [109] could have a profound influence in the adoption of intercropping as a climate-smart farming practice. The major goal is empowering farmers to use the best growing legumes side by side with cereals to improve resilience to disease, pests, and extreme weather conditions and reduce the use of pesticides and fertilizers [114]. Likewise, the VALMEDALM project, funded by the Partnership for Research and Innovation in the Mediterranean Area (PRIMA) [115], also intends to empower farmers but more specifically for almond production of the Mediterranean. The project aims to identify intercropping practices and promote its implementation across the Mediterranean, aligned with economic and social aspects, as well as sustainable principles towards an adaptation to climate change.

Both projects are aligned to empower farmers to adopt more sustainable polyculture systems that reconcile economic profitability with ecological stewardship and increased biodiversity.

4. Conclusions

Intercropping represents a transformative pathway toward achieving SDG 2 by harmonizing food security with environmental stewardship. Growing multiple crop species simultaneously increases agricultural diversity and fosters a more resilient production system, effectively breaking the uniformity of modern intensive farming. The use of intercropping in the Mediterranean region can be an option to increase crop production and quality, soil quality and microbiome and weeds and pests and control regarding monocropping systems. Also, in terms of economic effects, intercropping can increase gross energy and use less land, making it a promising strategy for the sustainable intensification of agricultural systems. As a potentially labor-intensive technique, it still faces challenges and limitations. The transition to large-scale adoption faces significant hurdles, primarily regarding labor intensity and mechanization gaps in seeding, weed management, and harvesting. To bridge the gap between scientific evidence and field adoption, future efforts must prioritize long-term economic assessments, scalability under climate change, and the integration of intercropped products into modern value chains. Ultimately, success depends on a participatory approach that involves farmers directly, overcoming their wariness through demonstrable profitability and localized policy incentives.

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