

Review

# Intercropping Systems: An Opportunity for Environment Conservation within Nut Production

Bruna Moreira <sup>1,2,3</sup>, Alexandre Gonçalves <sup>4</sup> , Luís Pinto <sup>4</sup> , Miguel A. Prieto <sup>3,\*</sup> , Márcio Carochó <sup>1,2</sup> ,  
Cristina Caleja <sup>1,2,\*</sup>  and Lillian Barros <sup>1,2</sup> 

<sup>1</sup> Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal; brunapcarvalhom@gmail.com (B.M.); mcarochó@ipb.pt (M.C.); lillian@ipb.pt (L.B.)

<sup>2</sup> Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

<sup>3</sup> Nutrition and Bromatology Group, Department of Analytical Chemistry and Food Science, Instituto de Agroecología e Alimentación (IAA)–CITEXVI, Universidade de Vigo, 36310 Vigo, Spain

<sup>4</sup> MORE—Collaborative Laboratory Mountains of Research, Brigantia Ecopark, 5300-358 Bragança, Portugal; agoncalves@morecolab.pt (A.G.); luis.pinto@aquavalor.pt (L.P.)

\* Correspondence: mprieto@uvigo.es (M.A.P.); ccaleja@ipb.pt (C.C.)

**Abstract:** Global population growth and intensive agriculture have both contributed negatively to the environment. As a result, there is increasing interest in the use of sustainable alternatives is increasing to promote better use of natural resources and create an equilibrium between agriculture and the environment. Intercropping, the simultaneous cultivation of multiple crops, aims to optimize land use economically while enhancing biodiversity through plant–microorganism interactions, thereby boosting crop productivity. This practice has particularly benefited nut production by combining the nutrient-sequestering capacity of trees with continuous annual crop production, improving soil nutrient and water utilization. Intercropping systems not only enhance nut yield and quality but also offer economic advantages to farmers. This review synthesized the existing literature with the aim of highlighting not only the positive aspects that intercropping brings to the production of nuts, but also the challenges and limitations faced in different regions when it comes to agricultural production.

**Keywords:** diversified crop cultivation; nuts; sustainability; biodiversity; polyculture; intercropping



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## 1. Introduction

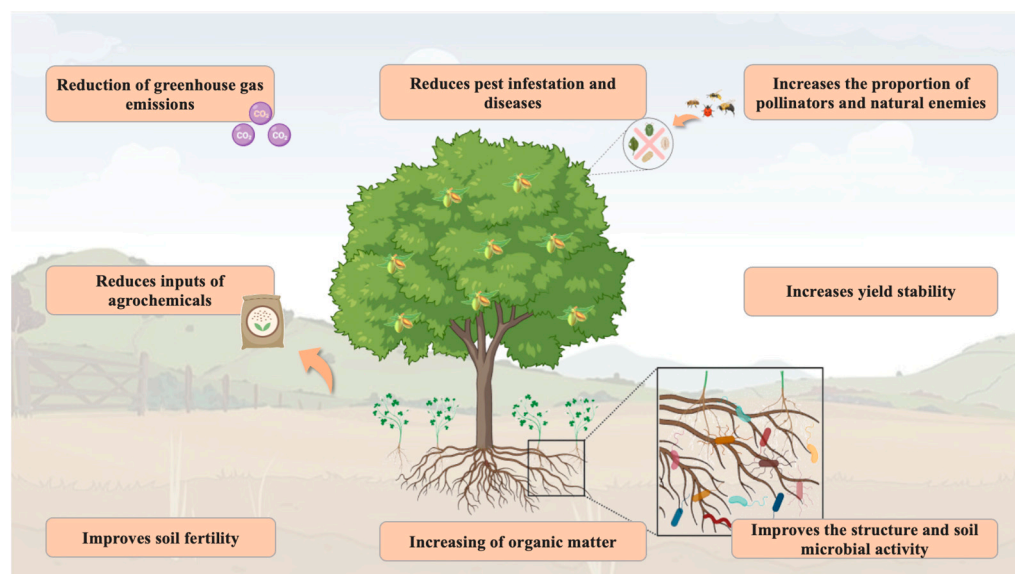
In recent decades, consumers have become aware of the importance of functional foods in their diet plan due to the increase in chronic diseases that have been their main concern [1]. For this reason, nuts have become the most popular snack, with a global market estimated at \$295.8 billion in the year 2022 and forecast to grow by 5.7% through 2030, reaching \$459.1 billion over the next 8 years [2]. This growth is due to their nutraceutical properties, as well as their unique flavor and, above all, their health-promoting bioactive compounds [3].

Nuts such as almonds, Brazil nuts, hazelnuts, macadamias, pine nuts, pecans, pistachios, and walnuts, are rich in minerals (e.g., calcium, magnesium, and potassium), high-quality protein, fiber, vitamins (e.g., folic acid, niacin, vitamin E and B6) and unsaturated fat specifically, monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA) [4,5]. These dry fruits are considered to be the main sources of procyanidins, one of the most abundant polyphenols in plants, which has been found to be beneficial for human health and used to prevent cancers, diabetes, and cardiovascular diseases [6]. It was reported by Balakrishna et al. [7] that, the consumption of 28 g/day of nuts reduced the risk of cardiovascular disease by 21%, cancer deaths by 11% and all-cause mortality by 22% compared to those who did not eat the nuts. However, the nutritional value of the nut

varies significantly according to the type of nut, the genotype, and the differences between cultivars [3]. Sokolow et al. [8], also pointed out that the nutrient content of food can change depending on the ecological and climatic conditions, such as temperature, rainfall, and solar radiation during growth [3]. To guarantee sustainable food production systems adapting to extreme climatic conditions, intercropping has become an excellent option for effective land use, by implementing agricultural practices that increase productivity [9].

Intercropping is considered an old agricultural practice technology that involves the planting of diversified crops with low input, improving the quality of the agroecosystem, thus focusing on food production in healthy environmental conditions [10,11]. Reportedly, the first agricultural settlements in South Asia (2500–2000 BCE) began using a double cropping system, with summer (wheat, barley, etc.) and winter (rice, etc.) crops grown in the same year. This period was marked by great agricultural development, stemming from the need to take advantage of the seasonal floods of the Ganges and its emerging rice plains [12].

Also known as mixed cropping or polyculture [11], intercropping aims for the efficient use of resources generated by the interrelationship between morphologically different crops, so that the result is an improvement in soil fertility through an increase in organic matter, as well as in crop yields [13,14]. In addition to these benefits, others can be generated from this agroecological approach such as, improving the management of diseases and pests and, meanwhile, increasing the proportion of pollinators and natural enemies due to the floral intercropping (Figure 1) [15,16]. Compared to monocultures, intercropping tends to increase yield stability, reduce inputs of agrochemicals through association with leguminous plants capable of fixing atmospheric nitrogen and, consequently, environmental costs through the reduction of water and soil pollution and greenhouse gas emissions [17].



**Figure 1.** Benefits generated by the interspecific relationship between crops in the intercropping system.

Among these strategies, the tree system has proven to be a tool to support agricultural production, playing a substantial role in reducing the atmospheric concentration of  $\text{CO}_2$  through the carbon sequestration power of trees, besides continuing to produce annual crops, and reducing soil erosion [18,19]. In addition, trees play another fundamental role in intercropping systems by modifying the microclimate, reducing radiation on the plant, thus forming a barrier against the force of the wind and temperature oscillations [20]. Agroforestry, which consist of growing woody vegetation (trees or shrubs) with plant and/or animal production systems, has become a practice used by farmers around the

world due to the constant availability of food, fruit, timber, fodder, and fuelwood, which has created sustainability in their livelihoods [21,22].

Regarding the categories of agroforestry systems, intercropped fruit trees [23] are used in the nuts production system, with the exception of peanuts, which is botanically classified as a legume. Nutritionists and consumers have included them in the nuts group because of their similar nutritional composition [24]. Research confirms the benefits generated by the intercropping of nuts and other crops, where the levels of soil nutrients such as nitrogen, phosphorus, potassium and organic matter, were significantly higher in walnut–tea intercropped forests than in monocrops [24].

However, many factors affect the balance of this system, where competition between species for resources, such as water, light and nutrients, can become crucial for the overall productivity of agroforestry intercrops [20,25]. Therefore, the main challenge for agriculture is to adopt tillage strategies that guarantee the long-term stability of agroecosystems, with an emphasis on preserving and improving soil health [26]. There are still several limitations that need to be analyzed in order to improve the deficiencies of this system, with the aim of allowing global food production to grow in a more sustainable way.

## 2. Features and Advantageous of Intercropping System

The intercropping system consists of a mixture of crops of different species grown in the same field, with the aim of achieving more sustainable and profitable crop cultivation. Intercropping generates several benefits for the agricultural ecosystem, such as the increased use of natural resources like water and nutrients, the greater conservation of resources and the promotion of soil biodiversity [27]. According to Maitra et al. [11], in order to maximize benefits from this system, farmers must consider suitable intercropping and management practices, planting geometry, and the operation of intercropping and plant protection.

### 2.1. Improvement in the Soil Quality

The intercropping system generates a positive impact on soil quality, including increased and maintained soil organic matter, nitrogen fixation when the crop is associated with a legume in the system, increased phosphorus availability and reduced erosion by providing more soil cover [28]. Researchers consider the intercropping system a suitable option because it manages to produce more on a smaller area of land compared to monoculture [29,30]. In addition to land use, intercropping can increase organic matter [31], and enzyme activity [32] and, improve structure [33] and soil microbial activity [34]. Roohi et al. [33] also highlighted that the practice of intercropping, combined with the use of fertilizers containing organic additives, has the potential to improve the structural integrity of the soil, promote the sequestration of soil organic carbon and ensure optimum crop production.

Sharma and Banik [35] revealed that the intercropping system of baby corn tested with four several plant species such as chickpea, pea, groundnut, and lentil provided advantages in increasing the economic yield due to the rise in the number of cobs/pods per plant. Regarding soil, the intercrop improved soil fertility in terms of nitrogen, phosphorus and potassium availability, organic carbon, cation exchange capacity, soil enzymes, microbial respiration, and microbial biomass carbon. In addition to the above benefits, intercropping also helps to reduce soil erosion, where excessive runoff can result in infertile soils with unproductive characteristics for farming systems.

Roots play an important role in this function, as deeper roots act in the deeper layers to retain soil moisture and nutrients. On the other hand, roots keep the soil on the surface, reducing erosion [36]. Diversity among crops and the healthy competition generated tend to increase the extent of root networks, leading to more efficient use of natural soil resources due to greater absorption [37,38].

Nyawade et al. [39] highlighted that intercropping with legumes reduces the loss of nitrogen from the soil, increases productivity and increases the efficiency of nutrient use. It

also improves drought resistance in shallow soil plants by encouraging deeper root growth, leading to higher growth rates and nutrient levels in leaves [40]. Crop diversification stabilizes yields under variable climatic conditions, leveraging beneficial interspecific relationships, optimizing resource use spatially, temporally or chemically [41]. This approach is essential, especially considering that multi-species agroforestry systems show remarkable potential for increasing agricultural productivity, thanks to the sequestration of organic carbon by trees [42].

This carbon sequestration occurs in the above-ground biomass, including stems, branches and foliage, and in the underground biomass, such as roots, in addition to the soil itself [43]. In the same way, these systems are effective at recovering nutrients from below the rooting zone of crops, promoting a more efficient and sustainable nutrient cycle [42]. Another function performed by agroforestry systems is the contribution to the mitigation of climate change, in which the sequestration of C should slow or even reverse the increase in atmospheric concentration of CO<sub>2</sub> [42]. Agroforestry systems not only influence the chemical and physical properties of the soil, but also the microbial population, making the soil more productive and the plant growing indirectly [44].

## 2.2. Biodiversity Conservation

In intercropping, the benefits generated in the agroecosystem also come from the increased biodiversity of microorganisms, which results in a greater concentration of nutrients for the soil, increasing its fertility [36]. In the intercropping system, biodiversity does not only apply to the soil, as crop mixtures tend to increase the population of different arthropods, insects and birds [11].

The research of Cai et al. [45] revealed that the highest abundance of arthropod predators was found in intercropping systems of Chinese cabbage with lettuce (141.67 predators/plot), presenting lower values when intercropped with green cabbage (97.67 predators/plot). This study aimed to elucidate the importance of intercropping in the conservation of natural enemies and in the ecological management of pests, making the system more sustainable for the environment.

Regarding the benefit of the plant interactions with microorganisms, this relationship can be divided into three categories, (i) microorganisms in association with plants that are responsible for providing nutrients, (ii) the groups of microorganisms that stimulate plant growth indirectly, by growth prevention or by the activity of pathogens, and finally, (iii) microorganisms responsible for direct plant growth, due to the production of phytohormones [46].

Microorganisms and enzymes act as regulators of soil health, as they are essential components that catalyze various biochemical processes, such as the decomposition of organic matter and the renewal of nutrients [47]. Soil enzymes such as urease, catalase and invertase catalyze the decomposition reactions of microorganisms, contributing to nutrient cycling and being important for plant maintenance [48,49]. Therefore, soil enzyme activity is strongly related to soil microbial functions, influencing the ability of soils to perform critical environmental functions, such as participation in biogeochemical cycles, where enzymes like  $\beta$ -glycosidases are related to an indicator of C cycling in soils, while urease, phosphatase and sulfatase are enzymes responsible for the generation of available N, P and S [49].

In agroforestry systems, microbial abundance is higher due to the influence of the trees, organic matter deposition and root exudates, thus creating a favorable environment for the increase of beneficial soil organisms such as nematodes, collembola, mites, diplopods, earthworms, fungi, and various insects are involved in carbon transformation and nutrient cycling [44].

## 2.3. Yield Stability

Production instability is one of the main negative points suffered by the monoculture system, due to its lower resistance to environmental disturbances and extreme climatic

conditions, such as frosts, droughts, and floods [36]. Climate change projects instability in the field, and significantly reduces yields in monocrops. The mixture of species in an intercrop may be the way to adapt crops that face these changes by providing the means to protect the plant against abiotic or biotic stresses suffered by them [50].

The stability of intercropping can be associated with an increase in biodiversity attributed to the relationship between crops, unlike monocultures. Intercropping offers greater production security, especially in high-risk areas, such as those subject to climate change, generating financial stability for farmers [36]. In farming systems with less use of pesticides or synthetic fertilizers, yield stability becomes more important, being higher compared to organic farming. However, profitability can suffer due to the high cost of inputs, in terms of seed costs and mechanization [50,51].

Madembo et al. [52] demonstrated that intercropping maize with jack bean and cowpea enhances yield stability compared to monoculture. This stability is attributed to nitrogen fixation by the intercropping system, weed suppression, and soil cover provided by cowpea, resulting in consistent yields across multiple growing seasons. Similarly, studies have shown that intercropping maize with legumes, particularly soybean, improves yield stability and nitrogen use efficiency, with maize–soybean rotations being notably stable [53]. Intercropping sugarcane with soybean has also proven effective in stabilizing soybean yields while reducing nitrogen fertilizer inputs by 40%, thereby lowering CO<sub>2</sub> and N<sub>2</sub>O emissions associated with synthetic fertilizers [54]. Further analysis by Raseduzzaman & Jensen [55] underscored that intercropping legume with cereals significantly enhances yield stability compared to monocropping, contributing to higher and more reliable crop yields. These findings highlight that increasing diversity through cereal–legume intercrops promote stability and enhances global food security efforts.

#### 2.4. Valorization of Bioactive Compounds

In order to produce healthier and more nutritious food, intercropping has become a more sustainable option, along with the use of N-fixing legumes, bio-fertilizers and biological control methods. Researchers have shown that intensive nitrogen fertilization has a negative effect on plant growth and biomass production, consequently interfering with the concentration of bioactive compounds [56]. To resolve this problem, Mohammadzadeh et al. [57] implemented a sustainable strategy using the intercropping of legumes with medicinal and aromatic plants. The results showed that intercropping improved essential oil content and quality by increasing compounds such as carvacrol, gamma-terpinene, p-cymene and carvacrol methyl ether. In addition, productivity was increased compared to monoculture cultivation.

Over a 5-year period, Rodríguez et al. [26] carried out experiments in an organic production system in a dryland almond orchard located in the Mediterranean region, assessing the impact of no-till and legume cover crops. An improvement in soil physical characteristics was observed with legume cover crops, including bulk density, water holding capacity and aggregate stability. Furthermore, there were improvements in chemical properties, such as an increase in soil organic carbon, nitrogen, potassium and micronutrient content, along with an increase in soil microbial activity. In summary, the implementation of mulch resulted in an increase in the antioxidant activity and total polyphenol content of the almonds, which contributed to improving their nutritional value.

In previous research, the intercropping of chicory (*Cichorium intybus* L.) with legumes resulted in a higher production of condensed tannins compared to monocrops, being 51.4 mg/g of TC in mixtures of Antler chicory and red clover (*Trifolium pratense* L.) and 30.9 mg/g of TC for Antler chicory monocrop. In addition, the intercropping system of chicory and red clover showed higher dry mass yield and forage of better nutritional quality compared to the solo chicory crop. Most of the condensed tannins produced were in the unbound form, suggesting that most of the forages evaluated would provide benefits for ruminant nutrition and health [58,59].

Wu et al. [60], reported in their study that intercropping green tea with Chinese chestnut obtained 100 differential positively regulated metabolites, including amino acids, organic acids, lipids, carbohydrates and flavonoids, in tea leaves from the intercropping system when compared to monocropping. Many of these compounds were responsible for the flavor and bioactivity, providing improvements in the quality of green tea, as well as benefits for human health.



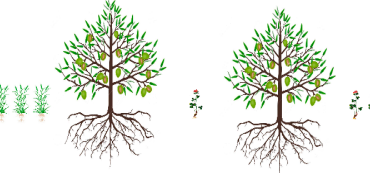
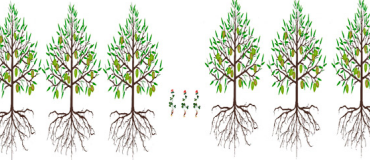
### 3. Types of Intercropping Systems

By growing genetically different plants, it is necessary to consider the factors that differ in each crop, such as crop maturity, planting time, irrigation, planting density, sunlight, and nutritional requirements [11,61]. There are also the abiotic factors (heat, cold, drought, salinity, among others) to which the crop is exposed during its growth, and these stress conditions lead the plant to adapt and create resistance mechanisms [62]. Each form of crop intercropping presents unique methods of planting, maintenance and harvesting to avoid competition between crop species. Therefore, there are various types of intercropping systems to suit planting conditions, such as mixed, row, relay and strip cropping systems [28].

#### 3.1. Mixed Intercropping

This intercropping practice consists of sowing two or more plant species on a plot of land, co-existing with each other without any defined proportion between rows [11,28]. As it is a system that consists of a greater number of crops in an area, it can bring benefits to the crop depending on the type of species, where it will provide resistance to abiotic and biotic stresses, as well as an increase in biodiversity, protecting the primary crop from the wind, frost, drought and other severe weather conditions [61,63]. According to Pan & Qin [64], mixed cropping was shown to be effective in pest control due to the increase in natural enemies. Specifically, three predators—ladybirds, lacewings, and hoverflies—increased compared to monocultures, resulting in a decrease in herbivores (aphids, leafhoppers, and whiteflies) in soybean cultivation. One of the disadvantages of this system is the problem of selecting the correct herbicide (Table 1) in the case of the combination of cereals and legumes, which generates a variable yield at the end of the harvest and, consequently, is the limiting factor in the use of mixed intercropping in organic farming [65,66]. There is also the difficulty of developing appropriate management practices and sowing ratios, due to the mixture of roots, leaves, and microbiome, which can generate greater interspecific interactions between crops and, with this, undesirable competition [28].

**Table 1.** Types of intercropping considering their use, advantages and disadvantages in agricultural production.

Schematic	Uses	Advantages	Disadvantages
 <p data-bbox="241 549 456 574">Mixed intercropping</p>	<ul data-bbox="622 373 1093 542" style="list-style-type: none"> <li>• Temporary pasture and annual forages as part of a rotation;</li> <li>• Perennial pasture and hayfields;</li> <li>• Extending the grazing season;</li> <li>• Grain and pulse production;</li> <li>• Crop-livestock integrated systems.</li> </ul>	<ul data-bbox="1137 373 1608 542" style="list-style-type: none"> <li>• Reduces the risk of crop failure due to environmental stress;</li> <li>• Pest infestation of crops is greatly reduced;</li> <li>• Increases soil fertility and yields due to crop mix.</li> </ul>	<ul data-bbox="1653 373 2123 542" style="list-style-type: none"> <li>• Applying fertilizers and pesticides to individual crops is very difficult;</li> <li>• Harvesting and threshing of crops separately are not possible;</li> <li>• Crops compete fiercely for resources like water, sunlight, and space.</li> </ul>
 <p data-bbox="250 762 448 788">Row intercropping</p>	<ul data-bbox="622 612 1093 778" style="list-style-type: none"> <li>• Used in the production of cereals and pulses;</li> <li>• Staple crops;</li> <li>• Forage species;</li> <li>• Sugar cane;</li> <li>• Small-scale horticultural production.</li> </ul>	<ul data-bbox="1137 622 1608 762" style="list-style-type: none"> <li>• Lower seed expenses;</li> <li>• Better controlling of stubble;</li> <li>• Less work on the soil;</li> <li>• Easier control of weeds between the rows.</li> </ul>	<ul data-bbox="1653 609 2123 778" style="list-style-type: none"> <li>• Lower rate of crop competition with weeds;</li> <li>• Decreased yield in some situations;</li> <li>• Higher rate of evaporation from the soil surface;</li> <li>• Less water efficiency.</li> </ul>
 <p data-bbox="250 1059 452 1085">Relay intercropping</p>	<ul data-bbox="622 941 1093 1021" style="list-style-type: none"> <li>• Used in maize and soybean production;</li> <li>• Annual self-seeding legumes;</li> <li>• Rice—cauliflower—onion—summer.</li> </ul>	<ul data-bbox="1137 826 1608 1139" style="list-style-type: none"> <li>• Reduced need for soil tillage;</li> <li>• Better use of resources in farm management, such as labour, time and equipment;</li> <li>• Some diseases and insects appear to spread more slowly when crops are intercropped;</li> <li>• Better erosion control as a result of increased ground cover;</li> <li>• Reduced leaching of mineral N from the agricultural environment.</li> </ul>	<ul data-bbox="1653 852 2123 1114" style="list-style-type: none"> <li>• Inadaptable to extremely heavy, poorly drained or dry clay soils;</li> <li>• An increase in pests and nematodes is highly possible;</li> <li>• Some crops may be affected by early autumn frosts;</li> <li>• There may be potential expenditure on additional machinery, which requires rapid field operations.</li> </ul>
 <p data-bbox="250 1347 452 1372">Strip intercropping</p>	<ul data-bbox="622 1251 1093 1305" style="list-style-type: none"> <li>• Grain and pulse production;</li> <li>• Annual and perennial forage crops.</li> </ul>	<ul data-bbox="1137 1203 1608 1343" style="list-style-type: none"> <li>• Allows the use of optimal agricultural techniques and makes it possible to harvest separately for each species;</li> <li>• The soil is filtered into the runoff through the strip with the nearby crop.</li> </ul>	<ul data-bbox="1653 1203 2123 1343" style="list-style-type: none"> <li>• Limits the efficient use of machinery, so it is not suitable for highly mechanized systems;</li> <li>• One crop may host a plant disease and pest that is harmful to the other crop.</li> </ul>

### 3.2. Row Intercropping

Row cropping is the cultivation of crops planted in a single or double row, allowing for interspecific interactions such as root-mixing, shading and competition for water and nutrients (Table 1) [11,28]. Positive points worth highlighting in this system are that intercropping in rows has the potential to alter the light environment to improve overall interception by crops [67], help minimize soil erosion [68], decrease surface runoff and reduce soil nutrient loss [69].

Experiments carried out by Perdoná and Soratto [70] evaluated the growth and productivity of a macadamia plantation, as well as the profitability and investment return period during 7 years of cultivation. The treatments consisted of two types of cultivation: macadamia in monoculture and macadamia–coffee in intercropping, with irrigation methods varying between dry and drip. Organized in a  $2 \times 2$  row arrangement, both the consortium with arabica coffee and drip irrigation resulted in the greater vertical growth of the macadamias, reaching 5.41 m for both systems, compared to 3.76 m in irrigated macadamia monocropping.

A study conducted by Lu et al. [71] examined the effects of different configurations of row proportions and strip widths in intercropping systems. Five treatments were tested in a field study: maize soil (SM), peanut soil (SP), four rows of maize interspersed with eight rows of peanuts (M4P8), four rows of maize interspersed with four rows of peanuts (M4P4) and four rows of maize interspersed with two rows of peanuts (M4P2). The results showed that the M4P8 configuration presented the highest yield and land use efficiency, offering substantial yield benefits with the increase in the proportion of peanut rows. Compared to the other intercropping systems, the M4P8 treatment showed a significant increase of 40.99% compared to the M4P4 treatment and 79.01% compared to the M4P2 treatment.

### 3.3. Relay Intercropping

Relay intercropping is the cultivation of two or more crops at the same time during part of the growing period of each, being planted and harvested at different times (Table 1). In this system, the crop is rotated for periods, that is, while the first crop completes its life cycle, close to being harvested, the second crop is sown [11,28]. According to Glaze-Corcoran et al. [28], competitive inhibition can be reduced with the better coordination of the life cycles of different crops through relay intercropping. Other features, such as the extended period of individual growth and the recovery period between the two cultures, are part of the process of this system.

Amossé et al. [72] reported that the success of the application depends on the choices between cereals and legumes, in function of the competitiveness generated between them. According to Raza et al. [73], the productivity benefits of relay intercropping systems are many times greater than other types of intercropping because crops do not have to compete for nutrients, light or water due to rotation. In an experiment formulated by Fan et al. [74], they showed that the maize–soybean relay strip planting system had a significant increase in relation to the uptake of nutrients such as nitrogen, phosphorus, and potassium, which may lead to greater crop development. Chen et al. [75] also reported that dry matter is a determining factor for nitrogen concentration in the crop, differing between species due to growth state and photosynthetic variations.

### 3.4. Strip Intercropping

Strip cropping can be defined as planting crops in parallel strips, where the strip width interferes with production yield (Table 1) [28,76]. According to the research conducted by Oort et al. [76], the benefits of intercropping decreased as strip width increased. This study also pointed out that wheat and corn intercropping obtained better results with widths of less than 1 m, which may be a limiting factor in relation to the use of machines with larger widths. In this system, crops can be harvested at the same time if cultivars of the same species reach the same maturity or, in the case of grain and legume crops, are harvested separately [28].

The studies conducted by Wang et al. [77] revealed that crop yields are affected by the variation in the proportion of border rows, influenced by the width of the strip, which varies from 1 to 4 m. Thus, strip width plays a crucial role in regulating plant interactions and relative yields in strip intercropping. Although wide strips in intercropping facilitate mechanization, increasing the width of the strip reduces the benefits of border lines at the field scale.

#### 4. Intercropped Species

Some requirements can be adopted to optimize the process of crop productivity through intercropping systems. For this purpose, it is necessary to increase the set of crop combinations already tested to know how they behave through the interspecific relationship, as well as to cultivate regional cultivars with complementary genotypes and to test plantings in different regions, since the dose of inputs is adjusted according to each crop [78,79]. Other practices can be adopted to obtain a more successful production: (i) select species that have the same water requirements; (ii) select plants that do not compete for sunlight; (iii) avoid grouping crops of the same family to mitigate pest invasion; (iv) sow herbs to obtain a repellent effect and attractive species to attract pollinators [61]. This is why it is so important to choose the species to be intercropped with the main production crop to achieve the efficient use of resources, high and stable yields, and sustainable agriculture.

##### 4.1. Legumes

In the intercropping system, legumes are valued for providing an important service to the field by reducing interspecific competition between crops by improving the exploitation of soil resource yields, reflected in increased productivity, and making the process more environmentally sustainable [9,80]. Intercropping with legumes has several positive effects such as biological nitrogen fixation in the soil, improving biodiversity, positively affecting the composition of rhizospheres, and thus increasing the availability of nutrients for plants [11,61]. Legumes are the only ones capable of obtaining free atmospheric nitrogen through symbiotic association with Rhizobia, which are nitrogen-fixing bacteria found in the root nodules of these plants. In addition to being available to the plant, this nitrogen also enriches the soil when the organic matter decomposes [81].

In the rhizosphere, microorganisms supply their host plants with essential assimilable nutrients, stimulate plant development by means of plant growth promoting bacteria (PGPB) and induce the production of antibiotics [82]. The intercropping of legumes with other crops such as maize, wheat, soybean, cowpea and fava bean results in improved nitrogen balance, P availability, root exudates, and increased microbial biomass and crop yield under stress conditions [9].

For the cereal–legume consortium to be successful in productivity, there are several conditions to be followed: (i) the periods of peak nutrient demand should not overlap (ii) there should be minimum competition for light between crops; (iii) there should be a complementarity between crops for the use of growth resources in time and space; (iv) there should be a difference in crop maturity of at least 30 days to reduce competition [83]. Research by Yu et al. [84] revealed that, through a meta-analysis of published studies, that the yield of cereals and legumes in a consortium is affected by seeding densities, seeding seasons and nitrogen fertilizers, which tends to reduce the yield of legumes in intercropping. Therefore, to increase food production, proper cultivation practices as well as the use of legumes at their maximum genetic potential and inoculation with compatible rhizobia are important [85].

Rodríguez et al. [26] evaluated the effect of legumes on almond production, analyzing various physical, chemical and biological aspects relevant to soil health and their implications for yield and the physical and chemical quality of the almonds. Three types of legumes were used as cover crops: fava bean (*Vicia faba* L.), vetch (*Vicia sativa* L.) and ervil (*Vicia ervilia* L.), to assess the influence of different soil management strategies. In terms of water capacity, the combination of *Vicia sativa* and *Vicia ervilia* (VS-VE) increased by more

than 21%, while the available water capacity of the soil increased by 23% at a depth of 10 to 25 cm. In terms of soil organic carbon (SOC) sequestration, the systems intercropped with *Vicia sativa* and VS-VE were statistically superior when compared to the system with fava beans. Long-term studies such as this one are essential to demonstrate how the use of mulch on crops such as dryland almonds can improve soil health and influence the nutritional composition of the almonds. This type of research is essential to promote sustainable agricultural practices and guarantee the quality of the food produced.

#### 4.2. Oilseeds

The intercropping of pulses and oilseeds seems to change the traditional agronomic scenario, where cereals and legumes, are the more common crops to be used in the environment. In studies conducted by Shah et al. [86], oilseed crops such as soybean, sesame, sunflower and Brassica were shown to suppress weeds through the production of different compounds in the air and rhizosphere by the release of isothiocyanates which are potent inhibitors of weed germination.

In other field trials, intercropping chickpeas with oilseed species of flax and canola resulted in yield maintenance or even yield increases in other cases compared to single crops. A significant reduction in fertilizer and fungicide inputs was also evaluated. In addition to production, intercropping an oilseed and a legume also offers other profit options for farmers, providing a high-quality hay or pasture option in years of low grain productivity [87].

The intercropping of legume/oilseed rape proved to be advantageous compared to monocropping in relation to maize biomass production and P uptake. Moreover, P uptake by intercropped maize averaged 0.58–0.92, significantly higher than biomass production (0.51–0.78), proving to be a resource that tends to exploit the biological potential of plants [88]. Other studies conducted on the intercropping of oilseed rape and legumes showed it to be advantageous with respect to yield and number of grains, being three times higher in the intercropping of oilseed rape (*Brassica napus* L.) with the faba bean (*Vicia faba* L.) compared to oilseed rape alone. Moreover, in this interspecific relationship, the above-ground biomass and N accumulation of weeds were reduced by 35% and 11%, respectively [89].

Regarding the structure of the microbial community, the intercropping of rape with white lupins (*Lupinus albus* L.) was able to enrich the rhizosphere with phosphorus solubilizing bacteria, such as *Streptomyces*, *Actinomadura* and *Bacillus*, and phosphorus solubilizing fungi, such as *Chaetomium*, *Aspergillus* and *Penicillium*. These phosphorus solubilizing microorganisms performed an important function in improving the uptake of this macronutrient in the soil. In addition to organic acids, 23 other metabolites from root exudates were significantly positively correlated with this microbial community established from the oilseed rape/white lupin intercropping system [90].

In addition to the increase in biodiversity, the oilseed intercropping system also contributes to the biological control of pests and the increase in the diversity of arthropod predators. Studies by Alarcón-Segura et al. [91] demonstrated a 50% reduction in wheat aphid densities and a 20% reduction in pollen beetle larvae in wheat and oilseed rape intercropping areas. An increase in carabid beetles was observed in canola strips and spiders in wheat strips in the intercropped area. In this context, the biological control implemented by the intercropping strips had a synergistic relationship among the system, causing a balance and, consequently, a decrease in the use of pesticides [91].

#### 4.3. Aromatic Plants

Also known as herbs and spices, aromatic plants began to be used thousands of years ago in the Middle East due to their preservative and medicinal properties, in addition to enhancing the aroma and flavour of foods [92]. They are plants rich in bioactive compounds, mainly polyphenolic, which promote antimicrobial, antioxidant, antiparasitic, antiprotozoal, antifungal, and anti-inflammatory activities [93,94].

Aromatic plants are characterised as perennials, flat growing, shade tolerant and adapted to dry and hot climatic conditions. Due to the increasing demand for products derived from aromatic plants, they become suitable for combining short-term returns with environmental benefits [95]. In response to abiotic and biotic stresses, the crop synthesizes considerable amounts of secondary metabolites and harvested plant materials, whether crude or processed, which are used in various applications in the food, cosmetic and pharmaceutical sectors [96,97].

Research has proven that intercropping with aromatic plants significantly increased soil organic matter and water content and decreased pH values. The exudates from the roots of aromatic plants, such as saccharides, lipids, organic acids, aromatic compounds, and amine, had the power to shape microbial diversity and promote enzymatic activities in the soil. In addition, it also regulated the nutrients C and N during the decomposition of soil organic matter [31].

Intercropping aromatic and medicinal plants (AMP) with nut trees in integrated management systems has been shown to have significant potential for increasing yields, and controlling pests/pathogens and weeds, as well as improving soil health and the quality of commercial crops [98]. The practice of diversifying into woody crops, such as almonds, offers a short-term annual balance of carbon (C) in the soil in semi-arid rainfed regions. This practice can be a sustainable strategy to reduce greenhouse gas (GHG) emissions in the soil and improve carbon sequestration and storage [99–101].

In studies carried out by Almagro et al. [101], the short-term effects on rainfed almond orchards (*Prunus dulcis* Mill.) grown under semi-arid Mediterranean conditions were evaluated, in intercropping with an aromatic plant such as thyme (*Thymus hyemalis* Lange). The results showed that diversification with winter thyme improved the aggregate stability of the soil and the availability of water for the plants. It also increased the organic carbon content of the topsoil from  $3.7 \text{ gkg}^{-1}$  in the first year to  $4.6 \text{ gkg}^{-1}$  in the third year of production. This highlights the importance of choosing species that provide carbon and plant cover all year round, such as winter thyme, to improve water regulation and soil formation.

#### 4.4. Vegetables

Vegetables in intercropping systems improve nitrogen utilization and uptake, and complementary root growth and therefore can increase productivity by mixing complementary species in terms of resource usage. The research showed that beans grown in a monoculture system had a higher risk of nitrate leaching because their roots have shallow growth, reducing N uptake in the deep soil layers. On the other hand, the crop associated with the vegetable increased the intensity of roots in the bean rows, playing an important role in the use of soil resources [102].

Other intercropping systems were proven advantageous with respect to economic returns. Yield loss decreased with an increasing proportion of legumes in potato intercropping systems (in patterns of 1:2.4), which generated higher economic gain from intercropping compared to monocropping, indicating a benefit ratio: cost of 4.98 versus 4.55 for pure potato stand. The productivity of the intercropped systems was higher due to the harvest being carried out at different times. This is due to the fact that dolichos (*Lablab purpureus* L.) were still in the flowering phase, which allowed them to take advantage of the moisture present in the soil and the nutrients resulting from the mineralization of harvested potato waste, resulting in an excellent yield [103].

Studies conducted by Hu et al. (2020) [104], demonstrated that the association of cauliflower with grasses brought the effect of soil salinity control and nitrate reduction by the vegetable, associated with the capacity of absorption and accumulation of salts and nitrates of the grass species. The species that obtained the most significant results of soil salinity control was *Paspalum vaginatum*, which reduced 37.8% of nitrate content, increased 50.7% of vitamin C and increased 21.1% of soluble protein in cauliflower curd.

Research has shown that plants also perform other functions in intercropping systems, such as reducing competition for light and for production factors, which is favourable for plant development [105]. Besides nitrogen, other nutrient elements may increase with intercropping, such as P, K, Ca, Mg, Mn and Zn, according to the intercropped crop species, compounds that are important for plant growth and development [106].

Grass species have been used to increase productivity and make yields more sustainable. Grass/wolfberry intercropping systems have increased the nutrient content and enzymatic activity of rhizosphere soils. This change was reflected in a 21% increase in carotenoids ( $0.41 \pm 0.05$  g/kg), a 56% increase in flavonoids ( $2.32 \pm 0.48$  g/kg) and, a significant 127% increase in fruit ascorbic acid ( $0.50 \pm 0.05$  g/kg) compared to wolfberry monoculture. The association of grasses with other plants aims to maximize their productivity and the beneficial effects they produce on the soil, rendering this interaction favourable to the environment [107].

## 5. Successful Intercropping Systems

In terms of nut production, intercropping plays a crucial role in sustainable environmental conservation, providing significant benefits (Table 2) [20,108–110]. The integration of nut trees with other crops in agroforestry systems not only improves productivity, but also contributes to the preservation and improvement of the agricultural ecosystem. Furthermore, this practice provides additional sources of income and increases food security [111]. These agroforestry systems provide a variety of agricultural products that can be harvested throughout the year, diversifying farmers' sources of income and making them less dependent on a single crop. This not only helps to mitigate the risks associated with price fluctuations and adverse weather conditions, but also promotes the economic resilience of rural communities [112].

The research conducted by Abbasi Surki et al. [113] showed the effects of the almond-cereal agroforestry system on wheat and barley grain crops, in which the highest yields were 2985 and 2180 kg ha<sup>-1</sup>, respectively. These results were obtained by arranging the trees in rows over the crops at a distance of 2.5 m between the systems, and the grain yields of wheat (35%) and barley (39%) were higher than their respective monocultures. Following the research of Abbasi Surki et al. [114], higher carbon contents (56 t ha<sup>-1</sup>) were detected in the agroforestry plots 0.5 m from the almond tree rows, doubling those of the wheat and clover monoculture. During the 8 years of research, it was observed that both the moisture retained in the field and the soil organic carbon content were higher for crops close to almond trees, especially for barley, where they were 28% and 1.82%, respectively.

Abourayya et al. [115] evaluated not only the chemical properties and fertility of the soil, but also the growth and nutritional status of almond trees (*Prunus amygdalus* B.) intercropped with snap bean (*Phaseolus vulgaris* L.), with a planting space of 5 × 5 m cultivated under a drip irrigation system. The results showed that intercropping had a significant effect on the vegetative growth characteristics of the almond trees, recording greater stem length and diameter, number of branches, number of leaves, leaf area, and fresh mass and dry mass of leaves, compared to almond trees grown alone. As far as the soil is concerned, incorporating snap bean into the soil improved the levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) exchangeable in both growing seasons.

**Table 2.** Successful intercropping systems on nut production.

Nuts	Intercropped Crops	Positive Effects	Refs.
Almond ( <i>Prunus dulcis</i> Mill.)	Legume cover ( <i>Vicia faba</i> L., <i>Vicia sativa</i> L. and <i>Vicia ervilia</i> L.)	<ul style="list-style-type: none"> <li>Improved the physical, chemical (soil organic carbon content, N, K and micronutrients) and biological (increased microbial activity) properties of the soil.</li> <li>Improved the nutritional value of the almonds by increasing antioxidant activity and total polyphenol content.</li> </ul>	[26]
Almond ( <i>Prunus amygdalus</i> B.)	Snap bean ( <i>Phaseolus vulgaris</i> L.)	<ul style="list-style-type: none"> <li>The intercropping treatment had a significant impact on the nutrient composition of leaves, particularly in terms of nitrogen, phosphorus and potassium percentages. Additionally, it also resulted in higher total chlorophyll content when compared to a single tree system.</li> </ul>	[115]
Almond ( <i>Prunus dulcis</i> Mill.)	Caper ( <i>Capparis spinosa</i> L.) and thyme ( <i>Thymus hyemalis</i> L.)	<ul style="list-style-type: none"> <li>Both crops significantly reduced CO<sub>2</sub> emissions from the soil;</li> <li>Thyme cultivation significantly increased the moisture content and organic carbon of the soil compared to monoculture, due to its perennial nature.</li> </ul>	[99]
Walnut ( <i>Juglans</i> spp.)	Tea ( <i>Camellia sinensis</i> L.)	<ul style="list-style-type: none"> <li>Improved the soil's nutritional conditions by increasing soil nitrogen, phosphorus, potassium and organic matter;</li> <li>Increased bacterial and fungal diversity, including Proteobacteria, Bacteroidetes, Firmicutes, Chlamydiae, Rozellomycota and Zoopagomycota in higher proportions.</li> </ul>	[116]
Areca nut ( <i>Areca catechu</i> L.)	Pandan ( <i>Pandanus amaryllifolius</i> Roxb.)	<ul style="list-style-type: none"> <li>Areca nut and pandan intercropping cultivation had a positive impact on soil microbial diversity and dynamic balance.</li> </ul>	[117]
Peanut ( <i>Arachis hypogaea</i> L.)	Millet ( <i>Setaria itálica</i> L.)	<ul style="list-style-type: none"> <li>The net income of the millet/peanut intercrop was the highest, reaching 2479 USD ha<sup>-1</sup>, representing an increase of 13.5% over the millet and 8.6% over the groundnut monocrop.</li> </ul>	[107,118]
Macadamia ( <i>Macadamia integrifolia</i> Maiden & Betche)	Coffee ( <i>Coffea arabica</i> L.)	<ul style="list-style-type: none"> <li>Macadamia nut production in an intercropping system irrigated with coffee was 251% higher than the rainfed macadamia monocropping.</li> <li>Intercropping with arabica coffee contributed positively to macadamia growth, regardless of the use of drip irrigation.</li> <li>Intercropping increased the number of fruits by 32% and the production of nuts in shell per tree by 30% compared to monoculture, increasing macadamia production.</li> </ul>	[70]

Table 2. Cont.

Nuts	Intercropped Crops	Positive Effects	Refs.
Cashew ( <i>Anacardium occidentale</i> L.)	Mango ginger ( <i>Curcuma amada</i> Roxb), elephant foot yam ( <i>Amorphophallus paeoniifolius</i> (Dennst.)), turmeric ( <i>Curcuma longa</i> L.), east Indian arrowroot ( <i>Curcuma angustifolia</i> Roxb), taro ( <i>Colocasia esculenta</i> (L.))	<ul style="list-style-type: none"> <li>The cashew and turmeric intercropping system recorded significantly higher cashew equivalent yield (3521.58 kg ha<sup>-1</sup>) being attributed to the higher yield of turmeric.</li> <li>The land equivalence ratio and production efficiency of the cashew + taro intercropping system were higher compared to the other systems, being 1.67 and 54.80 kg/ha/day, respectively.</li> </ul>	[119]
Peanut ( <i>Arachis hypogaea</i> L.)	Sugarcane ( <i>Saccharum officinarum</i> L.)	<ul style="list-style-type: none"> <li>The rhizosphere soil of the intercropped peanut had a higher pH and nutrient content (P, K and N) than the soil of the monocultured peanut.</li> <li>The sugarcane/peanut intercrop significantly increased the activities of acid phosphatase and urease in the rhizosphere soil, which are essential for the nitrogen cycle and the hydrolysis of phosphorus compounds in the soil.</li> </ul>	[120]
Peanut ( <i>Arachis hypogaea</i> L.)	Maize ( <i>Zea mays</i> L.)	<ul style="list-style-type: none"> <li>Land use efficiency was significantly increased in the three treatments with two, four, and eight rows of peanut intercropped, when compared to monocultures of peanut and maize.</li> </ul>	[71]
Peanut ( <i>Arachis hypogaea</i> Linn.)	Maize ( <i>Zea mays</i> L.)	<ul style="list-style-type: none"> <li>The yield of intercropped peanuts was directly proportional to the number of strips, with an average of 98.4 gm<sup>-2</sup> for M8P8. In comparison, this result was significantly higher than in M4P4, with an increase of 30%, and M2P2, with an increase of 99%.</li> </ul>	[77]

Integrating perennial cultivation with other crops in agroforestry systems can be an effective strategy for reducing CO<sub>2</sub> emissions from the soil, without harming production, while increasing the overall productivity of the agroecosystem [99]. For this reason, Sánchez-Navarro et al. [99] implemented a diversified almond intercropping system with *Capparis spinosa* L. and the aromatic species *Thymus hyemalis* Lange. The orchard was kept dry, but the thyme and capers were irrigated on four occasions to ensure proper establishment. The results showed that thyme significantly increased soil moisture when compared to monoculture, by 11.1% and 10.2% respectively. Thyme also showed significant improvements in soil carbon sequestration, with its values increasing from 3.85 g/kg in 2019 to 4.62 g/kg in 2021.

Another study involving intercrops with nuts confirmed that the integration of different crops significantly increased bacterial and fungal diversity compared to monoculture forests. Bai et al. [116] examined changes in soil physicochemical properties, enzyme activity and microbial community composition when walnut (*Juglans* spp.) was intercropped with tea plants (*Camellia sinensis* L.) in a forest system, comparing the results with a monoculture walnut and tea system. Bacterial and fungal diversity increased significantly as a result of intercropping, compared to tea and walnut monocultures, with the most abundant being *Proteobacteria*, *Bacteroidetes*, *Firmicutes*, *Chlamydiae*, *Rozellomycota* and *Zoopagomycota*. As a result, through intercropping, there was an increase in the presence of beneficial organisms responsible for nutrient cycling, protection against disease and improving abiotic stress.

The research conducted by Zhong et al. [117] also investigated soil microbial communities, as well as their effects on environmental factors, by establishing a field experiment in randomized blocks of pandan (*Pandanus amaryllifolius* Roxb) intercropped with areca nut (*Areca catechu* L.). The results showed that intercropping significantly improved soil bacterial indices, reducing organic carbon and total phosphorus content. Soil microbial communities such as *Firmicutes*, *Methylomirabilota*, *Proteobacteria*, *Actinobacteria*, *Chloroflexi*, *Verrucomicrobia* and *Ascomycota* responded significantly to changes in planting methods. These results suggest that intercropping with pandanus positively influences soil microbial homeostasis in areca nut plantations in the long term.

Perdoná and Soratto [70] conducted additional investigations to examine the growth, productivity and economic viability of the macadamia crop when grown in association with coffee, under two different irrigation systems: rainfed and drip irrigation. These results showed that intercropping resulted in higher macadamia production than monoculture, with a yield of 536 kg ha<sup>-1</sup> compared to 197 kg ha<sup>-1</sup> for the intercropped and monoculture systems, respectively.

Through the results obtained by Perdoná and Soratto [121], it was shown that intercropping with macadamia trees increased the productivity of Arabica coffee beans by 10% compared with monoculture under drought conditions. When combining drip irrigation and intercropping, the crop was more profitable, being 276% more than the monoculture irrigated coffee after the first five harvests. Ramteke et al. [119], presented data favourable to the system in which cashew in combination with taro (*Colocasia esculenta*) recorded the highest yield of 210.61 q/ha, compared to 4.18 q/ha from the cashew cultivation alone. In addition, a production efficiency of 54.80 kg/ha/day was obtained.

Regarding pest control, the intercropping of cashew and banana resulted in a significant decrease in the attack of the chestnut moth (*Anacampsis phytomiella* Busck), with 5.8% of the nuts punctured compared with the other treatments. It is assumed that this reduction in the number of pests is due to the degree of shading that the banana trees provide, which prevents the formation of a more favourable environment for the moth population [122].

Studies by Žalac et al. [20] showed that intercropping was more productive (28.986 € ha<sup>-1</sup>) than the separate production of field crops and walnut trees for all tree density scenarios in the first 6 years, with a difference in net margin of 1.435 € ha<sup>-1</sup>. Other research has proven the benefits of intercropping in walnut production, where results revealed that the composition and structure of the soil bacterial community changed significantly with the

intercropping of walnut/hairy vetch (*Vicia villosa* Roth.) compared to clear tillage. Soil microorganisms from this interspecific relationship were also found to have a potential for nitrogen cycling and carbohydrate metabolism, and may be related to the functions of *Burkholderia*, *Rhodopseudomonas*, *Pseudomonas*, *Agrobacterium*, *Paraburkholderia* and *Flavobacterium* [123].

Furthermore, a walnut intercropping system was shown to increase soil bacterial diversity, with *Firmicutes*, *Proteobacteria*, *Actinobacteria* and *Acidobacteria* being the dominant soil bacterial phyla. Soil pH and soil density were significantly correlated with bacterial diversity [124]. According to studies by Wu et al. [60], the intercropping of tea (*Camellia sinensis*) with Chinese chestnut influenced the amino acid metabolism of the crop, positively modifying the taste of the tea. The quality of the tea may be associated with the levels of allantoic acid, sugars, sugar alcohols and oleic acid, which were higher and the flavonoids less bitter in the intercropping system when compared to the monocropping system. Previous research confirmed the positive effect of intercropping chestnut (*Castanea mollissima* Blume) on tea (*Camellia sinensis* L.) production, where this crop integration has shown promise for tea quality and quantity. It had an effect on reducing the content of amino acids and catechins, while increasing theanine and caffeine, making the tea more refreshing and tastier [32].

Although taxonomically classified as a legume of the fabaceae family, peanuts (*Arachis hypogaea* L.) are also considered within the oilseed group due to their chemical composition [125]. Studies by Tang et al. [120] showed that pH, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium were higher in the soil of a sugarcane–groundnut intercropping system compared to peanut monocropping system. It is also worth noting that the intercropping of sugarcane and groundnut also significantly increased the activities of acid phosphatase and urease in the rhizosphere soil, having a positive effect on improving the soil nutrition of groundnut.

The intercropping of sugarcane and peanut makes the most of the land resources by increasing nutrients in the soil through the rise of beneficial microorganisms, renewal of organic matter and cycling of compounds such as nitrogen and phosphorus. In addition to bringing economic benefits to farmers, it contributes to the development of efficient and sustainable production [120].

Another investigation into peanut production in intercropping was carried out by Wang et al. [77]. They tested four different combinations of intercropped crops, all with equal proportions of maize and peanuts, but varying the number of rows per strip: M2P2 (two rows of maize to two of peanuts), M4P4, M6P6 and M8P8, as well as maize soil (SM) and peanut soil (SP). The results indicated that the most effective combination for peanut yield was M8P8, achieving  $98.4 \text{ gm}^{-2}$ . This highlights the influence of strip width on yield results. Evidence such as this promotes an improvement in the layout of rows during intercropping, further highlighting the viability of the strip system for sustainable intensification.

## 6. Challenges and Limitations for the Establishment of Service Crops

Despite its many benefits, intercropping also faces challenges and limitations in productivity between crops [15]. Often, the complexity and cost of management means that some farmers do not use this technique in the field [126]. The biggest challenges of this system are the lack of information on yield and crop performance in a mixture, the more complicated crop management and harvesting, and the economic risk associated with new combinations [127]. In some cases, multiple cropping systems can result in undesirable outcomes when crop selection is carried out erroneously as well as by geographical region [128].

Special bioactive chemicals (allelochemicals) released by plants can damage the growth and productivity of the other crop when they interact with each other, becoming a negative turnout of this relationship [11]. A case in point is that of the black walnut tree (*Juglans nigra* L.), the ideal tree species for intercropping due to its rapid growth and, production of high-

quality wood, as well as its ability to produce nuts. This walnut tree generates a detrimental effect on other plants, negatively affecting the growth of other species due to juglone, a chemical compound produced by this tree, which has an allelopathic effect on different crop species [129]. Research by Žalac et al. [130] showed that there was a 30% reduction in maize yield due to juglone excretion, which significantly reduced plant density. Jose & Holzmuelle [129] also pointed out in their research that some management techniques can reduce the allelopathic effects of juglone, including the use of polyethylene root barriers, the opening of trenches or discs and the planting and management of companion species during the initial establishment phase of black walnut.

A major disadvantage in intercropping is the difficulty in practical management of essential agronomic operations, particularly where farm mechanization is adopted or when the component crops grown in intercropping have dissimilar requirements for fertilizers, water, and plant protection requirements [11]. The use of machinery is very important in regular agronomic operations such as seeding, weeding or harvesting, and intercropping negatively interferes in the individual management of crops. Another setback is the need for more labour per unit area, which potentially leads to a decrease in yield if not effectively handled. This is found to be relevant in the case of maize–soybean intercropping, where mechanization proceedings lead to the damage of soybean, as it is harvested secondly and ends up being indirectly harmed due to the machinery use [131].

In agrosystems, the age of the tree also influences competition between species, because as the tree ages, interspecific competition increases, affecting the yield and physiology of the plant compared to the same plant grown in monoculture [132]. In relation to pest control, the intercropping system may face some risks in the potential of the intercrop, where some flowers may be toxic to predators [15]. In one instance, the pollen of *Lilium martagone* L. and *Hippeastrum* sp., which that caused 100% mortality of the predatory mite *Amblyseius swirskii*, was used as a biological control agent against several pests in greenhouses [133]. There is also the fact that the cover crop acts as a ‘green bridge’, tending to behave as a reservoir of pests and pathogens that can transfer to the following cash crop, ruining the main crop [134].

Solar radiation tends to be a limiting factor for agroforestry crops in many regions and can generate a reduction in yield by increasing shade, which can be solved by the regular pruning of trees to increase the light transmission rate [25,135]. Other agronomic measures can be taken to reduce the competition generated by the cropping system, such as adjustments between the rows of trees and crops, the selection of the most suitable crop variety, and root barriers, additional irrigation and fertilization should also be applied [25]. However, growing two or more crops together requires the careful planning of field operations and may require special interventions to reduce competition between the intercropped species, thus maintaining a balance [11].

## 7. Future Perspectives

Research has advanced in order to improve the crop proportions as well as the relationships of resource availability, capture and partitioning, thus leading to the better yield performance of the intercropping systems [136]. Other studies have also focused on expanding crop diversity and, signal-controlled interactions between intercrop species, analyzing below- and aboveground diversity relationships and developing functional, structural and empirical models for crop optimization [137]. Crop growth models based on mathematical processes have already been used in order to combine plant characteristics and environmental conditions in a systemic approach. Thus, they simulate the functioning of plants considering their individual properties and growing conditions, allowing for the evaluation of yields and genetic improvements in an accurate and efficient way, without relying on extensive field trials [138].

In this sense, research has been advancing to bring new resources to make intercropping systems more effective. In future studies, it will be necessary to focus on investigating the effects of intercropping on the composition and function of the microbial community,

focusing especially on the relationship between extracellular enzymes present in the soil and the genes responsible for encoding them. Long-term research is essential to deepen the understanding of the effects of subsurface processes on soil fertility, ecosystem stability and the contributions of sustainable agroecosystems to climate change adaptation and mitigation [139]. In addition, future dissemination efforts aimed at increasing the adoption of consortia systems can benefit from a more robust integration of farmers' perspectives in generating and providing information [140].

Regarding the quality of food from intercropping systems, there is still a lot of area for research, as the information available is limited. However, studies indicate that sustainably produced foods generally have lower amounts of nitrate residues, nitrites, pesticides, heavy metals and other pollutants harmful to human health. Furthermore, nutritional quality tends to be improved through this agricultural production system, resulting in greater antioxidant activity, vitamin content, total sugars and improved protein quality. Crop rotation proves to be more profitable and beneficial to the environment, in addition to being equally or even more nutritious. However, due to its lower yields and different costs, it is still a smaller alternative compared to conventional agriculture [141]. Therefore, the biggest challenge of intercropping systems in nuts is to select compatible crops to minimize competitive inhibition, allowing for easy field management and consequently increasing the profit compared to monocultures [28].

## 8. Conclusions

In the face of challenges in agriculture, such as the need to increase food production in relation to a growing population, steps are being taken to provide sustainable and profitable crop production through intercropping systems. Coupled with climate change, intercropping can be an option to increase crop production in nuts, especially as this interaction between crops can increase nitrogen and nutrient availability in the soil, provide yield stability and decrease nutrient leaching and infestation by pathogens and weeds. As a potentially labor-intensive technique, it still faces challenges and limitations in production, because the success of this system depends on the interactions between the component species, available management practices and environmental conditions. Therefore, further research is needed to find the ideal growing conditions for each nut species, as well as to find suitable crops that can generate high quality fruits from this interspecific interaction.

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