

Article

Impact of Cereal–Legume Intercropping on Changes in Soil Nutrients Contents under Semi–Arid Conditions

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Abstract: Cereal–legume intercropping systems are not well studied under the semi–arid conditions of Southern Tunisia. Therefore, the present study aimed to investigate the effect of intercropping durum wheat (*Triticum turgidum* ssp. durum L.) with chickpea (*Cicer arietinum* L.) on crop grain yield and soil physicochemical proprieties such as carbon (C) and nitrogen (N) availability, microbial biomass nutrients (C and N) and plant nutrient content (N) in comparison to their monocultures. Field experiments were conducted during the 2020–2021 (EXP–A) and 2021–2022 (EXP–B) seasons in Medenine, Tunisia. The results revealed a significant augmentation ($p < 0.05$) in the total nitrogen proportions (N_{tot}) within the soil of intercropped durum wheat (DuWh–IR) compared to its monoculture (DuWh–MC). The observed variations amounted to 32% and 29% during the two growing seasons, identified as EXP–A and EXP–B. Additionally, the soil of intercropped durum wheat (DuWh–IR) significantly ($p < 0.05$) accumulated more total carbon (C_{tot}) than the monocrop (DuWh–MC) for both experiments, showing an increase of 27% in EXP–A and 24% in EXP–B. Simultaneously, the N– uptake of durum wheat significantly increased under the effect of intercropping, showing a rise of 26% in the EXP–A season and 21% in the EXP–B season. Similarly, the yield of durum wheat crops was comparatively greater in the intercropped plots as opposed to the monoculture crops, with variances of 23% in EXP–A and 20% in EXP–B. Intercropping cereals and legumes has the potential to enhance the soil fertility and crop production in the semi–arid regions of Southern Tunisia and contribute to environmental sustainability by reducing reliance on nitrogen fertilizers.

Keywords: chickpea; durum– wheat; N– uptake; carbon availability; crop yield



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1. Introduction

Tunisia's soils are undergoing substantial degradation, leading to a loss of fertility and a decline in the soil's ability to retain and infiltrate water. This soil degradation is expected to intensify in the coming years due to rapid population growth and increased demands for soil production, exacerbated by global phenomena such as climate change. This prompted Tunisian farmers to adopt modern strategies marked by a notable simplification of agroecosystems and the widespread use of chemical inputs. Unfortunately, this has yielded various adverse environmental effects, as documented by Tribouillois et al. [1]. One significant consequence has been the decline in ecosystem services, particularly in

water and soil resources, as highlighted by Glaze-Corcoran et al. [2]. These impacts include the chemical, physical, and biological degradation of soil, eutrophication of surface and groundwater, and the release of nitrous oxides, contributing to air pollution [3,4].

As a result, there is growing scrutiny of modern agriculture, urging the adoption of new agronomic solutions that are both efficient and environmentally friendly, aiming to mitigate negative environmental impacts, address resource scarcity (such as water and fossil energy), and adapt to climate change [5,6]. Within this framework, biodiversity emerges as a pivotal strategy for sustainable agriculture, preserving soil fertility, optimizing nutrient utilization, managing pest protection, and sustaining overall productivity [7,8].

One potential avenue in this regard is the adoption of intercropping systems. Intercropping involves cultivating multiple crop species simultaneously on a single plot of land, aiming to enhance the land utilization efficiency and ultimately achieve higher productivity levels [9,10]. This agricultural practice is grounded in ecological principles, specifically facilitation and complementarity [6,8]. Furthermore, intercropping systems combining legumes and cereals are widely acknowledged as highly efficient cropping systems with the potential to optimize the utilization of resources, particularly nitrogen and water [10,11]. Moreover, these systems have demonstrated increased resilience to abiotic stressors, such as drought, and offer effective strategies for weed, pest, and disease management without relying on herbicides [12–14].

Implementing this agricultural cropping system has a significant impact on various nitrogen transformation processes by influencing microbial processes, diversity, and community composition [15–18]. Consequently, due to the nitrogen fixation facilitated by legumes, intercropped cereals exhibit a reduced dependence on nitrogen fertilizers compared to those grown in monoculture.

Numerous studies have highlighted that intercropping systems involving cereals and legumes demonstrate an enhanced efficiency in utilizing nutrient resources, specifically carbon (C), nitrogen (N), and phosphorus (P), compared to conventional single-crop systems [19–22]. The intercropping system is one of the most useful practices in crop production, especially in areas with water and nutrient deficiencies in arid and semi-arid climatic zones. Previous studies have confirmed that this type of land use can result in higher-than-expected yields due to an increased use of soil nutrients and/or by suppressing crop pests [23–25].

Adopting a chickpea-based intercropping system certainly has the potential to improve the nitrogen nutrition and crop yield for associated cereals through biological nitrogen fixation [26]. Nevertheless, like other vegetables, the growth and nitrogen fixation of chickpeas can be influenced by abiotic factors such as drought, phosphorus deficiency, low-nitrogen soil, and biotic factors including pests, weeds, and diseases [27–31]. These stressors are particularly significant in the southern Mediterranean regions, to which Tunisia belongs, where the impact of these limiting variables is more pronounced [32–34].

The cereal-legume intercropping system is poorly studied in Tunisia, particularly in the southeastern region characterized by a semi-arid climatic, limited precipitation, and nutrient-deficient soils. Therefore, the objective of this study was to investigate crop performance and soil physicochemical proprieties under a durum wheat-chickpea intercropping system. We hypothesize that this practice enhances carbon (C) and nitrogen (N) availability, microbial biomass nutrients (C and N), and plant nutrient content (N) in comparison to the monoculture practice. This hypothesis is based on the premise that incorporating chickpeas (legumes) into nitrogen-poor soils increases soil nutrient levels through biological N_2 fixation. Consequently, this process results in increased microbial biomass and improved nutritional value in the intercropped plants relative to those grown in monoculture.

2. Materials and Methods

2.1. Experimental Site

Experimental trials were conducted over two agricultural seasons in two distinct fields within the Medenine region (33°46' N and 10°59' E) of southeastern Tunisia. EXP-A represents the agricultural season of 2020–2021, while EXP-B denotes the agricultural season of 2021–2022. The average annual temperature at both sites ranges from 21.5 °C to 22.6 °C, with an annual rainfall varying between 167.8 and 241.6 mm. The Mediterranean climate in Medenine is characterized by a cold winter and an extended, very hot and dry summer. The soil samples were taken from the top layer (0–20 cm), air-dried, and sieved (2 mm) in preparation for analyzing certain physicochemical properties before beginning the experiment. According to Mtimet et al. [35], the soil type is classified as alluvial soil, and exhibits a sandy-loamy texture, comprising 70.2% sand, 20.1% silt, and 8.7% clay fraction. This site has an alkaline pH, registering at 8.02, and possesses low organic matter (OM) content, measuring 1.21%. CaCO₃ is present, with a content of 21%. Furthermore, measurements of total phosphorus (P_{Tot}), Olsen-P, and total nitrogen (N_{Tot}) reveal deficiencies in these elements. The P_{Tot} level was found to be 5.95 mg.kg^{−1}. Olsen-P was recorded at a value of 0.51 mg.kg^{−1}, and the N_{Tot} level was measured at 3.58 mg.kg^{−1}.

2.2. Experimental Device

The study was conducted with a variety of chickpea (*Cicer arietinum* L. *Amdoun*) and a variety of durum wheat (*Triticum turgidum* ssp. *durum* L. *Simeto*) cultivated either in intercropping or in monoculture. The experimental design chosen in our study was in the form of a split-plot comprising three replications (blocks). Each micro-plot included one of the following treatments: chickpea monoculture (ChKp-MC), durum wheat monoculture (DuWh-MC), and durum wheat-chickpea intercropping (DuWh-IR and ChKp-IR) (micro-plots (4.5 m²) × 3 treatments × 3 replications). The total surface area of the experimental plot was 40.5 m², with each micro-plot allocated 4.5 m², and each micro-plot was located 1 m from the adjacent micro-plots (Figure 1). The grain density used for both experiments was 100 ± 5 grains per m² for pure chickpea (ChKp-MC), 250 ± 3 grains per m² for pure durum wheat (DuWh-MC), 50 ± 3 grains per m² for intercropped chickpea (ChKp-IR), and 150 ± 5 grains per m² for intercropped durum wheat (DuWh-IR). The seeds were sown in the third week of January for both growing seasons, with occasional manual weeding. Importantly, no chemical fertilizers or herbicides were applied throughout the entire experiment. For each experiment, before sowing, a 20 cm deep sample was taken from each micro-plot and mixed to obtain a single sample, designated as the control soil (S-Bulk).

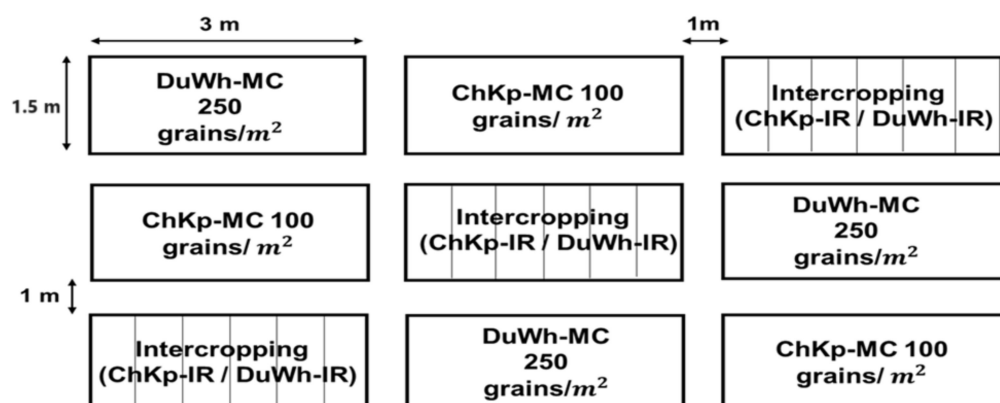


Figure 1. Experimental design including durum wheat-monocrops (DuWh-MC), chickpea-monocrops (ChKp-MC), and intercrops of durum wheat and chickpea (DuWh-IR and ChKp-IR).

2.3. Plant and Soil Sampling

At the full flowering stage (70 days after sowing), ten plants were sampled from each monocropped micro-plot, while five plants were sampled from each intercropped micro-

plot. The stems were detached from the roots at the cotyledonary node, subsequently dried at 60 °C for 48 h, and then weighed. Additionally, five soil samples from the rhizosphere were meticulously collected from the roots of each sampled plant. This soil, representing the fraction adhering to the roots (1–4 mm), was delicately recovered using a brush. The collected samples were blended to form a homogeneous mixture, then subjected to air-drying, followed by sieving to a particle size of 2 mm.

2.4. Measurements

The physicochemical analysis of the soils was conducted using standard methods from each site. The nitrogen content in both soil and plant samples were determined using the Kjeldahl method [36]. Soil pH was measured in a soil–water suspension (soil/water ratio = 1:2.5) using a pH meter. Phosphorus availability was assessed using the Olsen method [37], and the total phosphorus content in the soil was determined through the malachite green procedure following mixed digestion with perchloric and nitric acids [38]. Soil organic matter and soil carbon content were quantified using the Walkley and Black method [39], and the proportion of calcium carbonate (CaCO_3) in the soil was determined by measuring CO_2 volume based on the Horton and Newson methods [40]. Additionally, the nitrogen and carbon content in soil microbial biomass (SMB–N and SMB–C) were estimated using the fumigation extraction (FE) method devised by Vance et al. [41].

2.5. Statistical Analyses

The statistical analyses were performed using XLSTAT (Premium Version, 2019, Addinsoft, Long Island, NY, USA). Significant differences between mean values at $p = 0.05$ level of significance and the influence of treatments (intercropping and monocultures) on the variables (crop yield, nitrogen content in the soil (N_{tot}), plant N–uptake, soil microbial biomass fraction (SMB–N), soil carbon content (C_{tot}), and microbial biomass (SMB–C)) were investigated using the Tukey test.

3. Results

3.1. Crops Yield

The results depicted in Figure 2 indicate substantial crop yield variations in response to crop treatments (intercropping or monoculture) at both experimental sites. During the first season (EXP–A), there was a notable increase (23%) in the grain yield of durum wheat within the intercropped system compared to the monoculture. Similarly, during the second season (EXP–B), the grain yield of intercropped durum wheat showed a significant rise of 20% compared to the monoculture (Figure 2). Conversely, the grain yield of chickpea exhibited a significant decrease when intercropped with durum wheat in both EXP–A and EXP–B, with reductions of 21% and 17%, respectively, compared to its monoculture (Figure 2).

3.2. Nitrogen Content (N_{tot}) Soil Availability

Figure 3 illustrates the variation in soil nitrogen content (N_{tot}) in response to treatments and experimental sites during the two growing seasons. In both experiments EXP–A and EXP–B, the N_{tot} soil levels significantly increased for durum wheat under the influence of intercropping (DuWh–IR), showing a rise of 32% in EXP–A and 29% in EXP B compared to its monoculture (DuWh–MC). According to Figure 3, there was a notable reduction in N_{tot} ($p < 0.05$) observed in ChKp–IR compared to ChKp–MC across both sites, indicating a variance of 11% in EXP–A and 7% in EXP–B.

3.3. Soil Microbial Biomass (SMB–N) Variation

A notable increase ($p \leq 0.05$) in the nitrogen content of the soil microbial biomass (SMB–N) for intercropped durum wheat with chickpea (DuWh–IR) compared to its monoculture (DuWh–MC) was observed (Figure 4). This increase was approximately 39% and 36% during the EXP–A and EXP–B growing seasons, respectively. Furthermore, a slight decrease of approximately 5% in the nitrogen content of the soil microbial biomass for chickpea intercropped with durum wheat (ChKp–IR) compared to its monoculture (ChKp–MC)

in EXP-A was noted. However, no significant difference was observed between chickpea monocrops and chickpea intercrops during the EXP-B growing season.

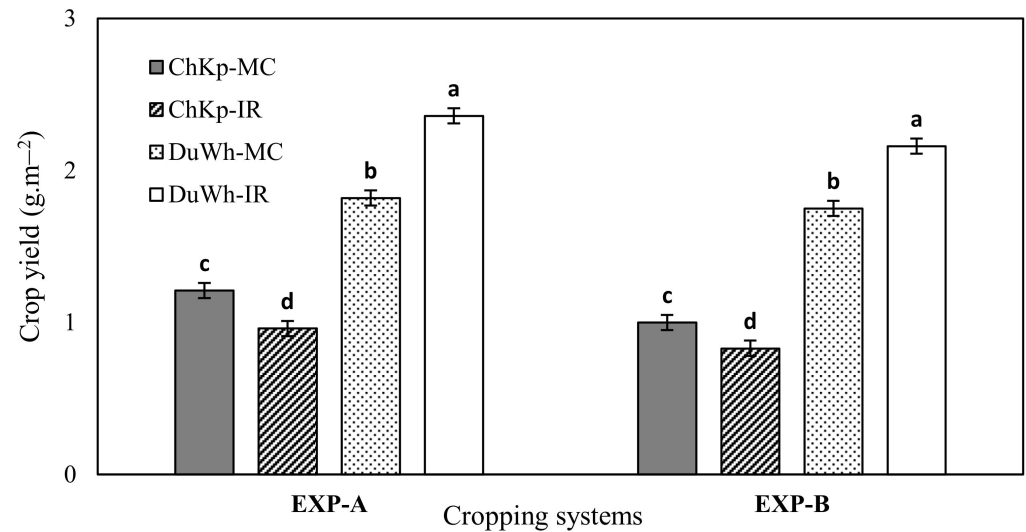


Figure 2. Grain yield levels (g.m^{-2}) of various crops, including chickpea–monocrops (ChKp–MC), durum wheat–monocrops (DuWh–MC), and intercrops of durum wheat and chickpea (DuWh–IR and ChKp–IR) were assessed over two years of cultivation (EXP–A and EXP–B). The error bars indicate the standard deviation. The letters a, b, c, and d represent the significant difference at a probability $p < 0.05$ between all treatments in each year.

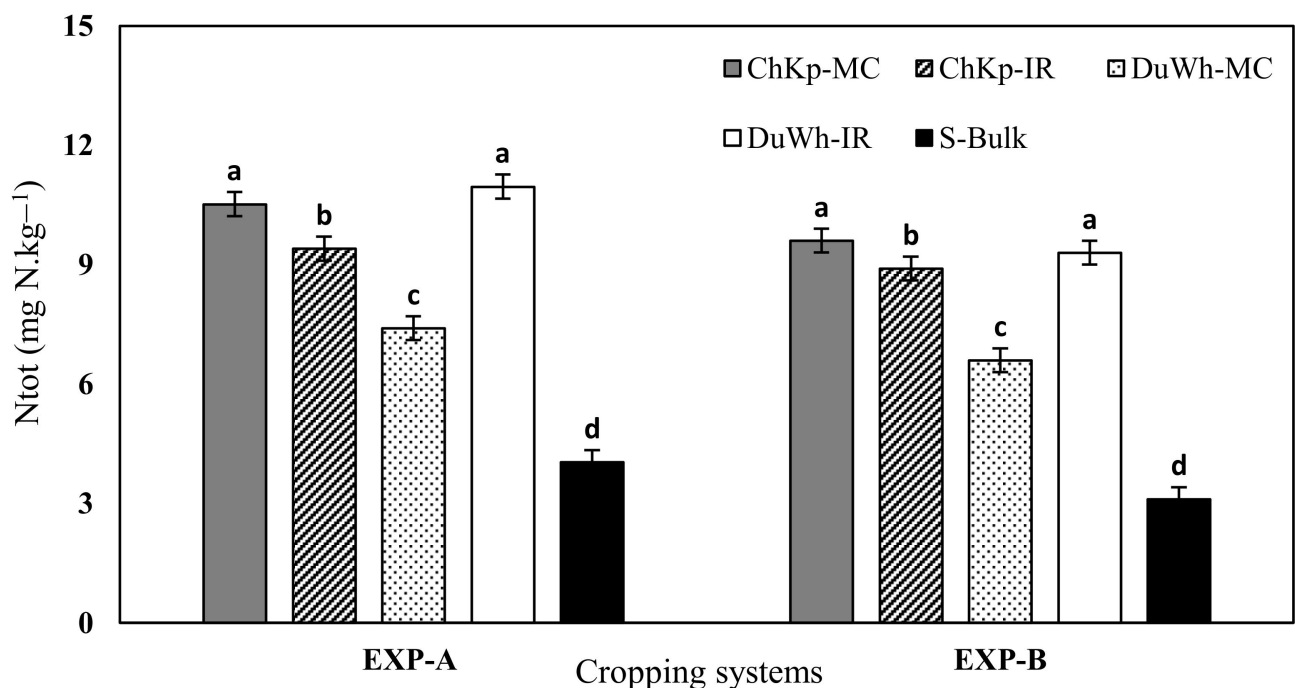


Figure 3. N_{tot} availability in the control soil (S–Bulk) and across the different crop covers (chickpea–monocrops (ChKp–MC), durum wheat–monocrops (DuWh–MC), and intercropped durum wheat–chickpea (ChKp–IR and DuWh–IR)) at the flowering stage during two growing seasons (EXP–A and EXP–B). The values are the average of three replicates. The error bars indicate the standard deviation. The letters a, b, c, and d represent the significant difference at a probability $p < 0.05$ between all treatments in each year.

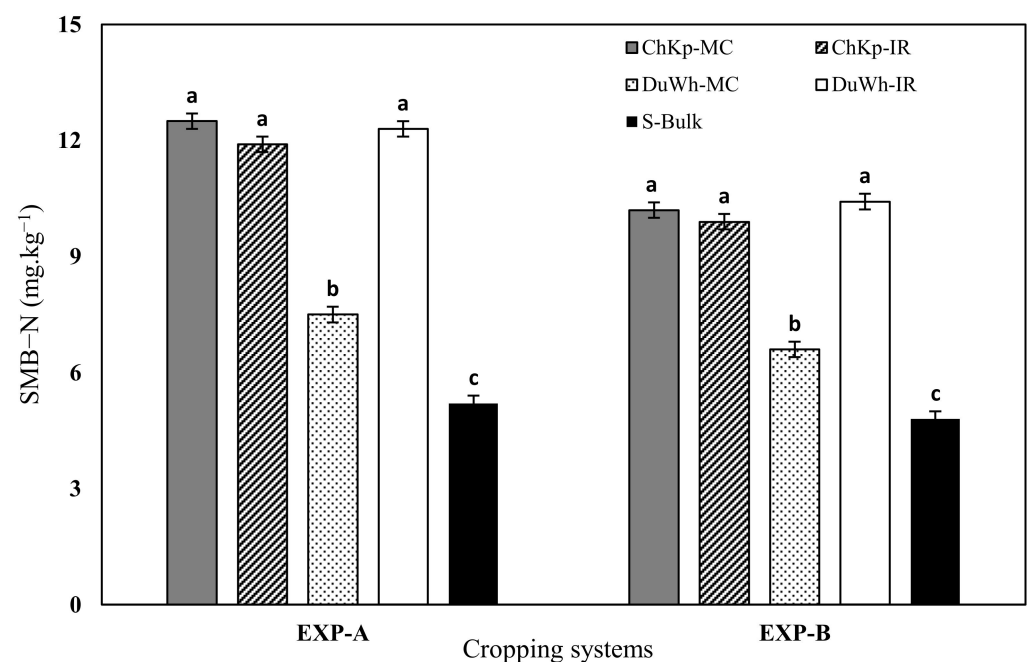


Figure 4. SMB-N variation in the control soil (S-Bulk) and across the different crop covers (chickpea monocrops (ChKp-MC), durum wheat monocrops (DuWh-MC) and intercrops durum wheat-chickpea (ChKp-IR) and (DuWh-IR) at the flowering stage during the two growing seasons (EXP-A and EXP-B). The values are the average of three replicates. The error bars indicate the standard deviation. The letters a, b, and c represent the significant difference at a probability $p < 0.05$ between all treatments in each year.

3.4. Nitrogen—Uptake

The results exhibited in Figure 5 indicate a significant decrease ($p < 0.05$) in nitrogen uptake (N-uptake) for intercropped chickpea (ChKp-IR) compared to its monoculture (ChKp-MC) for both experiments, with reductions of 13% for EXP-A and 10% for EXP-B. However, there was a significant increase ($p \leq 0.05$) in N-uptake for intercropped durum wheat (DuWh-IR) compared to the durum wheat monoculture (DuWh-MC); these increases were approximately 26% and 21% for EXP-A and EXP-B, respectively.

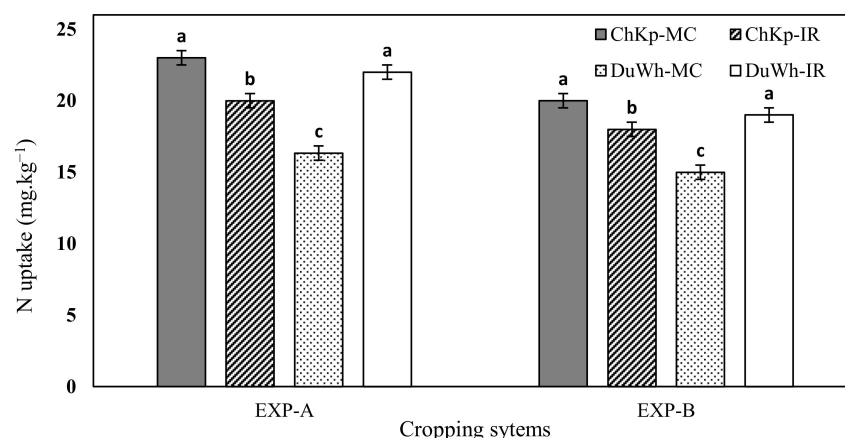


Figure 5. N-uptake by different crop covers (chickpea monocrops (ChKp-MC), durum wheat monocrops (DuWh-MC) and intercropped durum wheat-chickpea (ChKp-IR and DuWh-IR)) at the flowering stage, during the two growing seasons (EXP-A and EXP-B). The values are the average of three replicates. The error bars indicate the standard deviation. The letters a, b, and c represent the significant difference at a probability $p < 0.05$ between all treatments in each year.

3.5. Total Soil Carbon Content (C_{tot})

Figure 6 demonstrates that the soil carbon levels (C_{tot}) were significantly higher in the micro-plots with intercropped durum wheat (DuWh-IR) than in those with monoculture durum wheat (DuWh-MC) and the bulk soil (S-Bulk) across both experiments (EXP-A and EXP-B). In EXP-A, the C_{tot} concentration in DuWh-IR soil was 27% and 60% greater than in DuWh-MC and S-Bulk, respectively. For EXP-B, the increase in soil carbon content in DuWh-IR micro-plots was approximately 24% and 68% over DuWh-MC and S-Bulk, respectively. Nevertheless, there was no notable distinction detected among ChKp-MC, ChKp-IR, and DuWh-IR in both experiments, with 2.10%, 1.95%, and 2.01% in EXP-A and 1.74%, 1.62%, and 1.73% in EXP-B, respectively. Moreover, soil from the chickpea monoculture (ChKp-MC) demonstrated significantly higher carbon levels than those in the durum wheat monoculture (DuWh-MC) and bulk soil (S-Bulk) in both agricultural experiments. Specifically, in EXP-A, there was a 30% and 62% increase in total soil carbon content compared to DuWh-MC and S-Bulk, respectively. However, in EXP-B, increases in the soil carbon concentration were 24% and 68% relative to DuWh-MC and S-Bulk, respectively (Figure 6).

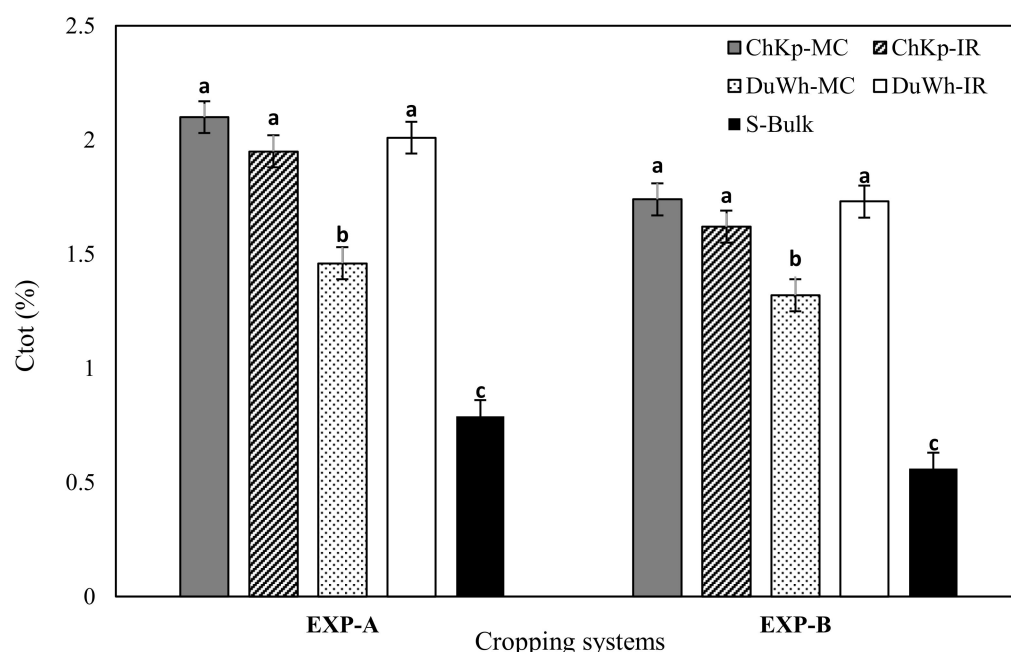


Figure 6. C_{tot} concentrations in the control soil (S-Bulk) and across the different crop covers (chickpea-monocrops (ChKp-MC), durum wheat-monocrops (DuWh-MC), and intercropped durum wheat-chickpea (ChKp-IR and DuWh-IR)) at the flowering stage during two growing seasons (EXP-A and EXP-B). The values are the average of three replicates. The error bars indicate the standard deviation. The letters a, b, and c represent the significant difference at a probability $p < 0.05$ between all treatments in each year.

3.6. Microbial Biomass (SMB-C) Variation

The carbon content variation in the soil microbial biomass (SMB-C) for the two years of experiments is demonstrated in Figure 7. During EXP-A, SMB-C concentrations in the soil cultivated with intercropped durum wheat (DuWh-IR) were significantly higher by 32% and 57% compared to the monoculture durum wheat (DuWh-MC) and the bulk soil (S-Bulk), respectively. Moreover, SMB-C concentrations obtained from the soil cultivated with pure chickpea (ChKp-MC) were significantly higher by 34% and 57% compared to the monoculture durum wheat (DuWh-MC) and the bulk soil (S-Bulk), respectively. Similarly, the results obtained in EXP-B aligned with those from the first experiment (EXP-A), indicating a significant increase in SMB-C of approximately 39% and 66% for the intercropped durum wheat (DuWh-IR) compared to the monoculture durum wheat

(DuWh–MC) and the bulk soil (S–Bulk), respectively. Additionally, for pure chickpea (ChKp–MC), SMB–C concentrations were notably higher by 36% and 67% compared to the durum wheat monoculture (DuWh–MC) and the bulk soil (S–Bulk), respectively.

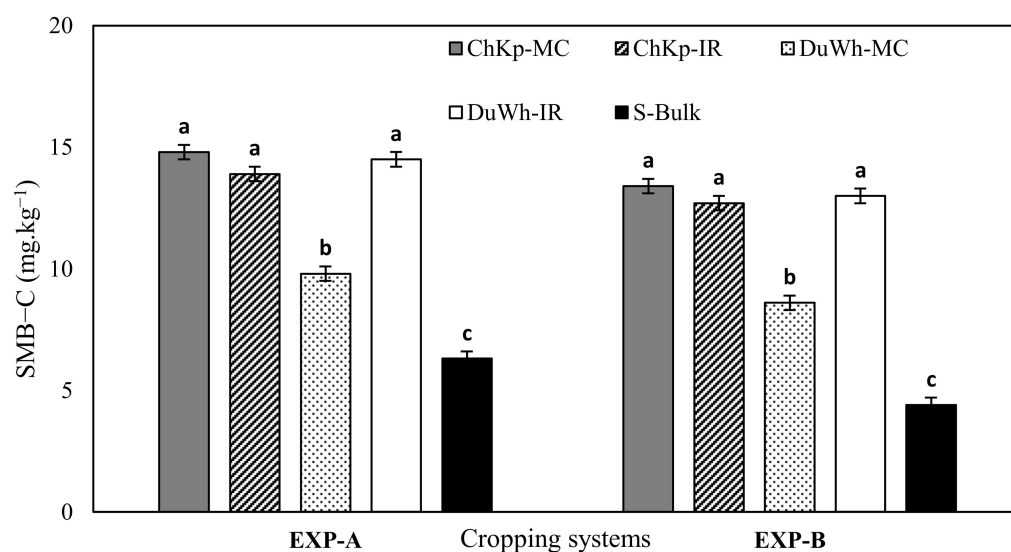


Figure 7. SMB–C content in the control soil (S–Bulk) and across the different crop covers (chickpea–monocrops (ChKp–MC), durum wheat–monocrops (DuWh–MC) and intercropped durum wheat–chickpea (ChKp–IR and DuWh–IR)) at the flowering stage during the two growing seasons (EXP–A and EXP–B). The values are the average of three replicates. The error bars indicate the standard deviation. The letters a, b, and c represent the significant difference at a probability $p < 0.05$ between all treatments in each year.

4. Discussion

4.1. Impact of the Durum Wheat–Chickpea Intercropping on Crop Yield

Cereal–legume intercropping’s effect on the crop yield has been extensively researched and documented across agricultural studies. This agricultural practice effectively enhances nitrogen levels in the soil, thereby directly influencing the grain yield [42]. These investigations highlight a notable increase in the cereal yield when intercropped with legumes, compared to being grown using monoculture practices. For instance, studies on maize [43] and durum wheat [44] have shown higher yields when intercropped with faba beans and soybeans, respectively. During both growing seasons (EXP–A and EXP–B), our findings demonstrated a marked rise in yield for the intercropped durum wheat (DuWh–IR). This enhancement was likely due to the efficient symbiotic nitrogen fixation facilitated by chickpea, resulting in greater nitrogen accumulation in the rhizosphere of the intercropped durum wheat. Similar increases in wheat yield within intercropping systems have been observed by Huñady and Hochman [45], who reported higher grain yields when wheat was intercropped with faba beans. Furthermore, Chhetri et al. [46] documented a 40% yield increase when wheat was intercropped with beans. This cropping system’s benefits in terms of enhancing cereal grain yields were reinforced by studies on wheat–maize intercropping, bean–maize intercropping [47], and cowpea–maize intercropping [48]. However, findings from the present study indicate a decrease in the yield of intercropped chickpea (ChKp–IR) when compared to their sole cultivation. This decline can be attributed to the vigorous interspecific competition with durum wheat for nitrogen resources, as reported by Latati et al. [49].

4.2. Effect of Intercropping Cereal–Legume Systems on the Availability of N_{tot} , N –Uptake, and Variations in N within the SMB–N

The primary findings depicted in Figures 3–5 highlight the substantial influence of the durum wheat–chickpea intercropping system on various aspects, including the total

nitrogen content of the soil (N_{tot}), nitrogen uptake by plants (N – uptake), and nitrogen present in the microbial biomass (SMB–N).

According to Figure 3, there was a substantial accumulation of N_{tot} in the rhizosphere of durum wheat intercropped with chickpea compared to its monoculture and N–deficient bulk soil across both experiments (EXP–A and EXP–B). This notable rise can most likely be attributed to the interspecific facilitation of nutrient utilization between durum wheat and chickpea. Moreover, legumes grown in an intercropping system enhance the availability of inorganic nitrogen in the rhizosphere through their ability for symbiotic nitrogen fixation (N_2), providing benefits to cereals [50,51]. These results are consistent with the findings of Hauggaard-Nielsen et al. [52], who noted a higher nitrogen concentration in the soil of peas, faba beans, and lupins when intercropped with barley compared to their monocultures. Similarly, Corre-Hellou et al. [53] demonstrated elevated nitrogen concentration in the soil under pea and barley intercropping as opposed to their monocultures.

However, the nitrogen (N_{tot}) content in the rhizosphere of monoculture chickpea remained elevated compared to the levels observed under the influence of intercropping, probably due to the strong competition from intercropped durum wheat for the absorption of nitrogen fixed by chickpeas in the soil [54]. This increase in N_{tot} within intercropped durum wheat through symbiotic nitrogen fixation was accompanied by a rise in the content of SMB–N in the rhizosphere of durum wheat (Figure 4). Thus, the SMB–N increase can be attributed to the transfer of nitrogen from nodules to the soil microbial biomass after nodule senescence, as reported by Latati et al. [19]. Furthermore, these findings align entirely with those of Tang et al. [55], who reported an increase in microbial biomass under the influence of the wheat/chickpea intercropping compared to their respective monocultures. However, the low nitrogen content in the microbial biomass obtained in the bulk soil (S–Bulk) may be explained by the absence of soil tillage and the addition of organic amendments to stimulate soil microbial activity [56].

Moreover, Figure 5 indicates a rise in the plant–absorbed nitrogen content (N – uptake) for durum wheat when in association compared to its monoculture in both experiments (EXP–A in 2020–2021 and EXP–B in 2021–2022). Our results are consistent with the findings of Zhang et al. [20], who reported an enhanced nitrogen content in wheat when cultivated in an intercropping system with soybeans compared to its monoculture. Likewise, Szumigalski and Van Acker [57] observed increased nitrogen concentrations in wheat and canola crops when intercropped with peas.

4.3. Effect of Cereal–Legume Intercropping Systems on C_{tot} Content and SMB–C Variation

Our results demonstrated a significant enhancement in the soil microbial biomass (SMB–C) of intercropped durum wheat compared to its monoculture and the bulk soil (Figure 6). This enhancement may be assigned to the combined root exudates from both chickpea and durum wheat. These findings align with those of Tang et al. [55], who observed enhancements in microbial biomass carbon stocks when durum wheat was intercropped with chickpea and lentils compared to their respective monocultures. Likewise, Latati et al. [19] documented a rise in the soil microbial biomass for maize and bean intercropping.

Another notable result from this study pertains to the soil carbon (C_{tot}) content, which underwent a significant increase during both cropping seasons (EXP–A and EXP–B) when durum wheat was intercropped with chickpea, compared to the monoculture and the bulk soil, as depicted in Figure 7. The significant soil carbon content observed may be attributed to the increased microbial activity favored by its intercropping with chickpea [58]. This occurrence has already been observed in various regions worldwide. For instance, Chapagain and Riseman in 2014 [59] observed similar results in Vancouver, Western Canada, for barley–pea intercropping, and Scalise et al. [60] found the same in an agroecosystem in Southern Italy for barley and bean intercropping. Thus, it is apparent that soil microbial biomass plays a crucial role in the mineralization of organic matter and the enrichment of the soil with carbon, which is an essential element for the proper development of crops.

5. Conclusions

The main results of this field research revealed an increase in durum wheat grain yields under the intercropping system compared to the monoculture. This increase can be attributed to a significant bioavailability of nitrogen (N) in the rhizosphere of intercropped durum wheat in the two sites that were characterized by initially low nitrogen soil contents. Furthermore, this study validates that intercropping durum wheat with chickpea enhances the soil carbon content compared to monoculture practices. This improvement stems from heightened microbial activity in the rhizosphere of the intercropped durum wheat, recognized as a pivotal mechanism in the mineralization and decomposition of soil organic matter.

Therefore, chickpea exhibits a beneficial impact in the context of interspecific competition in the intercropping system. Consequently, this study affirms the benefits of the durum wheat–chickpea intercropping system in improving soil fertility and crop yield compared to a monoculture, leading to a reduction in the reliance on chemical fertilizers. Finally, durum wheat–chickpea intercropping could offer a pragmatic solution to fostering sustainable agriculture in semi-arid regions.

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References

1. Tribouillois, H.; Dürr, C.; Demilly, D.; Wagner, M.H.; Justes, E. Determination of Germination Response to Temperature and Water Potential for a Wide Range of Cover Crop Species and Related Functional Groups. *PLoS ONE* **2016**, *11*, e0161185. [[CrossRef](#)] [[PubMed](#)]
2. Glaze-Corcoran, S.; Hashemi, M.; Saghpour, A.; Jahnazad, E.; Afshar, R.K.; Liu, X.; Herbert, S.J. Understanding intercropping to improve agricultural resiliency and environmental sustainability. *Adv. Agron.* **2020**, *162*, 199–256.
3. Ohyama, T. The role of legume-rhizobium symbiosis in sustainable agriculture. In *Legume Nitrogen Fixation in Soils with Low Phosphorus Availability*; Sulieman, S., Phan Tran, L.S., Eds.; Springer: Cham, Switzerland, 2017; pp. 1–20.
4. Andrés, P.; Doblas-Miranda, E.; Silva-Sánchez, A.; Mattana, S.; Font, F. Physical, Chemical, and Biological Indicators of Soil Quality in Mediterranean Vineyards under Contrasting Farming Schemes. *Agronomy* **2022**, *12*, 2643. [[CrossRef](#)]
5. Zuma, M.; Arthur, G.; Cooposamy, R.; Naidoo, K. Incorporating cropping systems with eco-friendly strategies and solutions to mitigate the effects of climate change on crop production. *J. Agric. Food Res.* **2023**, *14*, 100722. [[CrossRef](#)]
6. Lefebvre, M.; Midler, E.; Bontems, P. Adoption of Environment-Friendly Agricultural Practices with Background Risk: Experimental Evidence. *Env. Resour. Econ.* **2020**, *76*, 405–428. [[CrossRef](#)]
7. Pansu, M.; Ibrahim, H.; Hatira, A.; Brahimi, N.; Drevon, J.J.; Harmand, J.M.; Chotte, J.L.; Blavet, D. Modelling the continuous exchange of nitrogen between microbial decomposers, the organs and symbionts of plants, soil reserves, and the atmosphere. *Soil Biol. Biochem.* **2018**, *125*, 185–196. [[CrossRef](#)]
8. Rebouh, N.Y.; Khugaev, C.V.; Utkina, A.O.; Isaev, K.V.; Mohamed, E.S.; Kucher, D.E. Contribution of Eco-Friendly Agricultural Practices in Improving and Stabilizing Wheat Crop Yield: A Review. *Agronomy* **2023**, *13*, 2400. [[CrossRef](#)]
9. Vidal, D.F.; Trichet, P.; Puzos, L.; Bakker, M.R.; Delerue, F.; Augusto, L. Intercropping N-fixing shrubs in pine plantation forestry as an ecologically sustainable management option. *For. Ecol. Manag.* **2019**, *437*, 175–187. [[CrossRef](#)]

10. Bouras, F.-Z.; Hadjout, S.; Haddad, B.; Malek, A.; Aitmoumene, S.; Gueboub, F.; Metrah, L.; Zemmouri, B.; Kherif, O.; Rebouh, N.-Y.; et al. The Effect of Nitrogen Supply on Water and Nitrogen Use Efficiency by Wheat–Chickpea Intercropping System under Rain-Fed Mediterranean Conditions. *Agriculture* **2023**, *13*, 338. [\[CrossRef\]](#)
11. Kherif, O.; Haddad, B.; Bouras, F.-Z.; Seghouani, M.; Zemmouri, B.; Gamouh, R.; Hamzaoui, N.; Larbi, A.; Rebouh, N.-Y.; Latati, M. Simultaneous Assessment of Water and Nitrogen Use Efficiency in Rain-Fed Chickpea–Durum Wheat Intercropping Systems. *Agriculture* **2023**, *13*, 947. [\[CrossRef\]](#)
12. Corre-Hellou, G.; Crozat, Y. N₂ fixation and N supply in organic pea (*Pisum sativum* L.) cropping systems as affected by weeds and pea weevil (*Sitona lineatus* L.). *Eur. J. Agron.* **2005**, *22*, 449–458. [\[CrossRef\]](#)
13. Deveikyte, I.; Kadziulienė, Z.; Sarunaite, L. Weed suppression ability of spring cereal crops and peas in pure and mixed stands. *Agron. Res.* **2009**, *7*, 239–244.
14. Amossé, C.; Jeuffroy, M.H.; Celette, F.; David, C. Relay-intercropped forage legumes help to control weeds in organic grain production. *Eur. J. Agron.* **2013**, *49*, 158–167. [\[CrossRef\]](#)
15. Lian, T.; Mu, Y.; Jin, J.; Ma, Q.; Cheng, Y.; Cai, Z. Impact of intercropping on the coupling between soil microbial community structure, activity, and nutrient–use efficiencies. *Peer J.* **2019**, *7*, 6412. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Laranjeira, S.; Fernandes-Silva, A.; Reis, S.; Torcato, C.; Raimundo, F.; Ferreira, L.; Car-nide, V.; Marques, G. Inoculation of plant growth promoting bacteria and arbuscular mycorrhizal fungi improve chickpea performance under water deficit conditions. *Appl. Soil. Ecol.* **2021**, *164*, 103927. [\[CrossRef\]](#)
17. Williams, A.; Birt, H.W.G.; Raghavendra, A.; Dennis, P.G. Cropping System Diversification Influences Soil Microbial Diversity in Subtropical Dryland Farming Systems. *Microb. Ecol.* **2023**, *85*, 1473–1484. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Netthisinghe, A.M.; Galloway, H.O.; Agga, G.E.; Gunter, P.A.; Sistani, K.R. Effects of Cropping Systems on Soil Physicochemical Properties and Abundances and Spatial Distributions of Nitrogen–Cycling Bacteria. *Agronomy* **2023**, *13*, 1461. [\[CrossRef\]](#)
19. Latati, M.; Rebouh, N.Y.; Aouiche, A.; Laouar, M. Modelling the functional role of the micro-organisms in the daily exchanges of carbon and nitrogen in intercropping system under Mediterranean conditions. *Agron. Res.* **2019**, *17*, 559–573.
20. Homulle, Z.; George, T.S.; Karley, A.J. Root traits with team benefits: Understanding belowground interactions in intercropping systems. *Plant Soil* **2021**, *471*, 1–26. [\[CrossRef\]](#)
21. Singh, A.K.; Singh, J.B.; Singh, R.; Kantwa, S.R.; Jha, P.K.; Ahamad, S.; Singh, A.; Ghosh, A.; Prasad, M.; Singh, S.; et al. Understanding Soil Carbon and Phosphorus Dynamics under Grass–Legume Intercropping in a Semi-Arid Region. *Agronomy* **2023**, *13*, 1692. [\[CrossRef\]](#)
22. Wang, G.; Sheng, L.; Zhao, D.; Sheng, J.; Wang, X.; Liao, H. Allocation of Nitrogen and Carbon Is Regulated by Nodulation and Mycorrhizal Networks in Soybean/Maize Intercropping System. *Front. Plant Sci.* **2016**, *7*, 1901. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Willey, R. Intercropping: Its importance and research needs. 1. Competition and yield advantages. *Field Crops Abstr.* **1979**, *32*, 1–10.
24. Lal, B.; Rana, K.S.; Rana, D.S.; Shivay, Y.S.; Sharma, D.K.; Meena, B.P.; Gautam, P. Biomass, yield, quality and moisture use of Brassica carinata as influenced by intercropping with chickpea under semiarid tropics. *J. Saudi Soc. Agric. Sci.* **2017**, *18*, 61–71. [\[CrossRef\]](#)
25. Raza, M.A.; Yasin, H.S.; Gul, H.; Qin, R.; Mohi Ud Din, A.; Khalid, M.H.B.; Hussain, S.; Gitari, H.; Saeed, A.; Wang, J.; et al. Maize/soybean strip intercropping produces higher crop yields and saves water under semi-arid conditions. *Front. Plant Sci.* **2022**, *13*, 1006720. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Vandermeer, J.; van Noordwijk, M.; Anderson, J.; Ong, C.; Perfecto, I. Global change and multispecies agroecosystems: Concepts and issues. *Agric. Ecosyst. Environ.* **1998**, *67*, 1–22. [\[CrossRef\]](#)
27. Hamdi, W.; Noura, Z.; Ernest, K.; Blavet, D.; Seffen, M. Effect of the soils properties on the sorption capacity of phosphorus and ammonium by alkaline soils of the semi-arid areas. *IOSR-JA C* **2015**, *5*, 34–42.
28. Hamdi, W.; Hamdi, N.; Jellali, S.; Seffen, M. Effect of background electrolytes on the adsorption of phosphorus (P) onto southern Tunisia natural clays. *Phys. Chem. Earth* **2022**, *127*, 103160. [\[CrossRef\]](#)
29. Leoni, F.; Lazzaro, M.; Carlesi, S.; Moonen, A.C. Screening suitable legumes for living mulches to support nitrogen dynamics and weed control in a durum wheat-forage sorghum crop sequence. *Field Crops Res.* **2024**, *307*, 109246. [\[CrossRef\]](#)
30. Huss, C.P.; Holmes, K.D.; Blubaugh, C.K. Benefits and Risks of Intercropping for Crop Resilience and Pest Management. *J. Econ. Entomol.* **2022**, *115*, 1350–1362. [\[CrossRef\]](#)
31. Boudreau, M.A. Diseases in intercropping systems. *Annu. Rev. Phytopathol.* **2013**, *51*, 499–519. [\[CrossRef\]](#)
32. Brenas, S.V.; Celette, F.; Pissaloux, A.P.; David, C. Biotic and abiotic factors impacting establishment and growth of relay intercropped forage legumes. *Eur. J. Agron.* **2016**, *81*, 169–177. [\[CrossRef\]](#)
33. Kchaou, R.; Benyoussef, S.; Jebari, S.; Harbaoui, K.; Berndtsson, R. Forage Potential of Cereal–Legume Mixtures as an Adaptive Climate Change Strategy under Low Input Systems. *Sustainability* **2023**, *15*, 338. [\[CrossRef\]](#)
34. Delhoumi, M.; Zaabar, W.; Ben Rhouma, A.; Achouri, M.S. Effects of agricultural practices and abiotic factors on woody diversity across two agroecosystems in Tunisia. *Vie et milieu-life and environment* **2018**, *68*, 253–261.
35. Mtimet, A.; Lasram, M. *Atlas Des Sols Tunisiens*; Ministère de l’agriculture: Tunis, France, 1999.
36. Kjeldahl, J. A new method for the determination of nitrogen in organic matter. *Zeitschrift für Analytische Chemie* **1883**, *22*, 366–382. [\[CrossRef\]](#)
37. Olsen, S.R.; Cole, C.V.; Watanabe, F.S.; Dean, L.A. *Estimation of Available Phosphorus in Soils by Extraction with NaHCO₃*; USDA Cir.939; US Department of Agriculture: Washington, DC, USA, 1954.

38. Valizadeh, G.R.; Rengel, Z.; Rate, A.W. Response of wheat genotypes efficient in P utilization and genotypes responsive to P fertilization to different P banding depths and watering regimes. *Aust. J. Agric. Res.* **2003**, *54*, 59–65. [\[CrossRef\]](#)
39. Walkley, A.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [\[CrossRef\]](#)
40. Leo, M.W.M. Determination of soil carbonates by a rapidegasometric method. *J. Agric. Food Chem.* **1963**, *11*, 452–455. [\[CrossRef\]](#)
41. Vance, C.P.; Uhde-Stone, C.; Allan, D.L. Phosphorus acquisition and use: Critical adaptations by plants for securing a nonrenewable resource. *New Phytol.* **2003**, *157*, 423–447. [\[CrossRef\]](#)
42. Boulelouah, N.; Berbache, M.R.; Bedjaoui, H.; Selama, N.; Rebouh, N.Y. Influence of Nitrogen Fertilizer Rate on Yield, Grain Quality and Nitrogen Use Efficiency of Durum Wheat (*Triticum durum* Desf.) under Algerian Semiarid Conditions. *Agriculture* **2022**, *12*, 1937. [\[CrossRef\]](#)
43. Dahmardeh, M.; Ghanbari, A.; Syahsar, B.A.; Ramrodi, M. The role of intercropping maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* L.) on yield and soil chemical properties. *Afr. J. Agric. Res.* **2010**, *5*, 631–636.
44. Tang, X.; Yu, Y.; Shen, J.; Van der Werf, W.; Zhang, F. Intercropping legumes and cereals increases phosphorus use efficiency: A meta-analysis. *Plant Soil* **2021**, *460*, 89–104. [\[CrossRef\]](#)
45. Huňady, I.; Hochman, M. Potential of legume-cereal intercropping for increasing yields and yield stability for self-sufficiency with animal fodder in organic farming. *Czech J. Gen. Plant Breed.* **2014**, *50*, 185–194. [\[CrossRef\]](#)
46. Chhetri, B.; Sinha, A.C. Advantage of maize (*Zea mays*)-based intercropping system to different nutrient management practices. *Indian J. Agron.* **2020**, *65*, 25–32. [\[CrossRef\]](#)
47. Lazali, M.; Brahimi, S.; Drevon, J.J. High yields in a low-P tolerant recombinant inbred line of common bean under field conditions. *Rhizosphere* **2018**, *8*, 27–33. [\[CrossRef\]](#)
48. Takim, F.O. Advantages of maize-cowpea intercropping over sole cropping through competition indices. *J. Agric. Biodivers. Res.* **2012**, *1*, 53–59.
49. Latati, M.; Pansu, M.; Drevon, J.J.; Ounane, S.M. Advantage of intercropping maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.) on yield and nitrogen uptake in Northeast Algeria. *IJRAS* **2013**, *1*, 1–7.
50. Wehme, H.; De Guia, A.H.; Connor, M. Reduction of Fertilizer Use in South China Impacts and Implications on Smallholder Rice Farmers. *Sustainability* **2020**, *12*, 2240. [\[CrossRef\]](#)
51. Yong, T.W.; Ping, C.; Qian, D.; Qing, D.U.; Feng, Y.; Wang, X.; Liu, W.; Yang, W.Y. Optimized nitrogen application methods to improve nitrogen use efficiency and nodule nitrogen fixation in a maize-soybean relay intercropping system. *J. Integr. Agric.* **2018**, *17*, 664–676. [\[CrossRef\]](#)
52. Hauggaard-Nielsen, H.; Gooding, M.; Ambus, P.; Corre-Hellou, G.; Crozat, Y.; Dahlmann, C.; Dibet, A.; von Fragstein, P.; Pristeri, A.; Monti, M.; et al. Pea-barley intercropping for efficient symbiotic N₂-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. *Field Crops Res.* **2009**, *113*, 64–71. [\[CrossRef\]](#)
53. Corre-Hellou, G.; Fustec, J.; Crozat, Y. Interspecific competition for soil N and its interaction with N₂ fixation, leaf expansion and crop growth in pea-Barley intercrops. *Plant Soil.* **2006**, *282*, 195–208. [\[CrossRef\]](#)
54. Chen, S.; Waghmode, T.R.; Sun, R.; Kuramae, E.; Hu, C.; Liu, B. Root-associated microbiomes of wheat under the combined effect of plant development and nitrogen fertilization. *Microbiome* **2019**, *7*, 1–13. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Tang, X.; Bernard, L.; Brauman, A.; Daufresne, T.; Deleporte, P.; Desclaux, D.; Souche, G.; Placella, S.A.; Hinsinger, P. Increase in microbial biomass and phosphorus availability in the rhizosphere of intercropped cereal and legumes under field conditions. *Soil Biol. Biochem.* **2014**, *75*, 86–93. [\[CrossRef\]](#)
56. Chenene, Y.; Blavet, D.; Belalmi, M.; Kaci, G.; Teffahi, M.; Ounane, S.M. Variation of chickpea nodulation in a Mediterranean agroecosystem: Relationship with soil characteristics and thresholds for significant contribution to plant growth. *Agron. Res.* **2021**, *19*, 42–56.
57. Szumigalski, A.R.; Van Acker, R.C. Nitrogen yield and land use efficiency in annual sole crops and intercrops. *Agron. J.* **2006**, *98*, 1030–1040. [\[CrossRef\]](#)
58. Arshad, M. Fortnightly dynamics and relationship of growth, dry matter partition and productivity of maize based sole and intercropping systems at different elevations. *Eur. J. Agron.* **2021**, *130*, 126377. [\[CrossRef\]](#)
59. Chapagain, T.; Riseman, A. Barley-pea intercropping: Effects on land productivity, carbon and nitrogen transformations. *Field Crops Res.* **2014**, *166*, 18–25. [\[CrossRef\]](#)
60. Scalise, A.; Tortorella, D.; Aurelio, P.; Petrov, B.; Gelsomino, A.; Lindstrom, K.; Monti, M. Legume-barley intercropping stimulates soil N supply and crop yield in the succeeding durum wheat in a rotation under rainfed conditions. *Soil Biol. Biochem.* **2015**, *89*, 150–161. [\[CrossRef\]](#)

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