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Analysis on the Application of Intercropping in the Efficient Land Utilization of Leguminous Crops

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Abstract Intercropping is a key practice in sustainable agriculture, which aims to improve productivity and ecological balance by growing multiple crops in the same field. This study focuses on the integration of legumes in intercropping systems to improve land use efficiency. The theoretical basis of intercropping is systematically analyzed, emphasizing resource complementarity, niche differentiation and ecological intensification. Legume-based intercropping practice strategies, such as strip intercropping, relay intercropping and mixed intercropping, are further explored, and the agronomic, environmental and economic benefits of these strategies are evaluated. The practical applications and results are illustrated with case studies from East Africa, China and India. Despite the recognized advantages of intercropping, challenges such as labor complexity, mechanization limitations and knowledge gaps remain significant factors restricting its development. This study concludes that the integration of legumes through tailored intercropping methods can not only improve land productivity and soil health, but also contribute to sustainable intensification. Future development should focus on integrating precision agriculture, cultivating suitable varieties and strengthening policy support to scale up the application and improve its effectiveness.

Keywords Intercropping; Leguminous crops; Land-use efficiency; Ecological intensification; Sustainable agriculture

1 Introduction

Intercropping is the practice of growing two or more crops simultaneously on the same field. This approach makes better use of land and resources and can also increase crop yields. This practice is particularly useful in agricultural systems with low inputs. Through intercropping, land use is more efficient, harvests are more stable, and less pesticides and fertilizers can be used, which helps make agriculture more sustainable and contributes to global food security (Zhang et al., 2020; Roberts et al., 2021). Intercropping can also increase the variety of organisms in the field and reduce harm to the environment, such as reducing greenhouse gas emissions and improving soil (Pelzer et al., 2020; Diacono et al., 2021).

Legumes are very important in agriculture. They have a special ability to cooperate with bacteria in the soil to "transform" nitrogen in the air into nutrients that plants can use, so that less fertilizer is needed (Carlsson et al., 2020; Cao et al., 2024). Planting legumes in intercropping systems can make the soil more fertile, increase organic matter, and improve nutrient cycling, which is good for legumes and crops grown with them (Watson et al., 2024; Zhang et al., 2025). Legumes can also help suppress weeds, promote the growth of other crops, and make the planting system more resilient to risks, so they are very valuable in sustainable agriculture (Rajendran et al., 2022).

This study mainly wants to understand the role of intercropping technology in improving land use efficiency, focusing on the application of legumes. We will combine the current research results to look at the agronomic, ecological and economic benefits of legume intercropping systems, analyze its impact on soil health and yield, and discuss its potential to reduce inputs and improve sustainability under different agricultural conditions. Finally, we will also point out some current problems and unresolved research gaps, hoping to provide reference for the future development and promotion of legume intercropping.

2 Theoretical Foundations of Intercropping Systems

2.1 Principles of resource complementarity and niche differentiation

The core idea of intercropping is "resource complementarity". Different crops grow in the same field, and they use light, water, and nutrients in different ways and at different times, so they do not compete for resources. This practice can reduce competition and increase overall yields. Some crops are planted early and harvested early, some have deep roots, and some have shallow roots, so that the resources in the land can be more fully utilized, which is better than planting a single crop (Dong et al., 2018). For example, when legumes and cereals are planted together, if their growth periods only partially overlap, the "time difference" can be used to increase yields and land use efficiency (Zhang et al., 2020).

2.2 Role of facilitative interactions and reduced competition in legume-based intercropping

When legumes are planted with other crops, the helping effect between them is obvious. Legumes can 'grab' nitrogen from the air and convert it into nutrients in the soil, which also benefits surrounding crops (Figure 1). In this way, less nitrogen fertilizer can be applied (Li et al., 2020; Xu et al., 2021). Studies have found that a large part of the yield-increasing effect of legume intercropping comes from the "complementarity" between crops (Yasin et al., 2024), especially when fertilizer is used little or even no. As long as the right crop combination is selected and their planting spacing and location are arranged, this help will be more obvious and competition will be reduced.

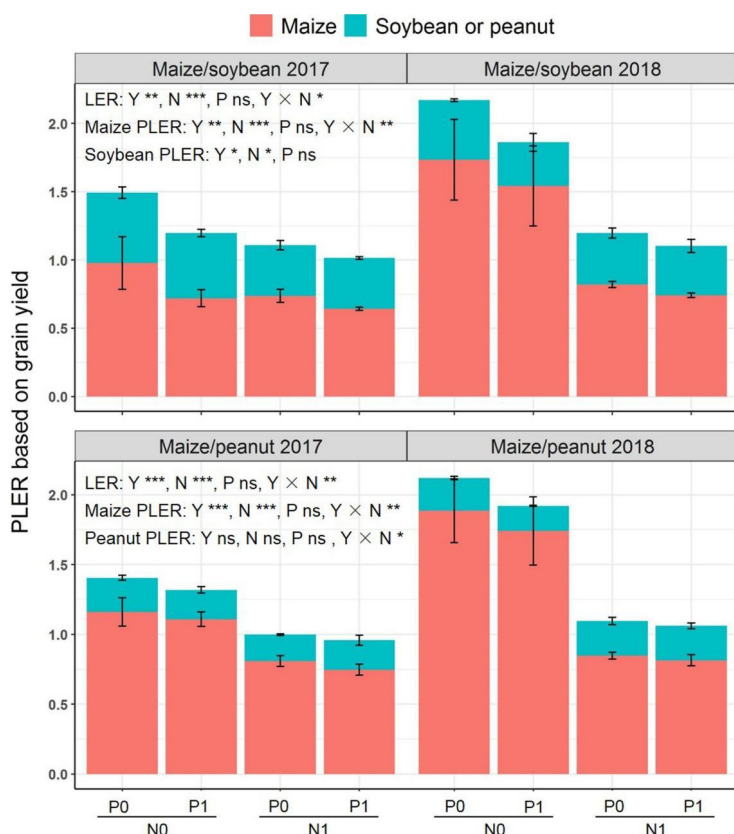


Figure 1 Partial land equivalent ratio (PLER) of maize, soybean and peanut in maize/soybean and maize/peanut intercropping, based on grain yield, in relation to N and P fertilization in 2017 and 2018. Note that 'N0' and 'N1' means no N and N fertilizer added, respectively. 'P0' and 'P1' means no P and P fertilizer added, respectively. Total LER is the sum of the two PLER for maize and legume (soybean or peanut). Data show means $\pm$ SEM of each crop ($n = 3$). * $p < 0.05$; ** $p < 0.01$; ns, not significant (Adopted from Xu et al., 2021)

2.3 Ecological intensification: maximizing productivity through spatial and temporal crop diversity

The so-called "ecological intensification" is to improve the yield and resource utilization efficiency by rationally arranging the planting time and spatial location of crops. Intercropping crops with different growth habits and

nutrient requirements can better absorb nutrients from the soil and improve resistance to problems such as pests and drought (De Mazancourt et al., 2022). There is a method called "4C" (competition, complementarity, cooperation and compensation) that can help us understand how these crops affect each other (Watson et al., 2021). In addition, arranging the proportion and planting layout of leguminous crops can further improve yields and resource utilization, increase income, and make agriculture more sustainable (Liu et al., 2024).

3 Intercropping Strategies Involving Leguminous Crops

3.1 Strip intercropping: arrangement, spatial benefits, and root zone management

To put it simply, strip intercropping is to plant leguminous crops and non-leguminous crops in strips. You can imagine a field where a strip of soybeans is planted first, and then a strip of corn is planted. The strips are close to each other but independent of each other. In this way, each crop stays in its own root zone to absorb water and fertilizer safely, and can share excess resources at the junction of the strips. The design of the strips allows for more uniform sunlight exposure, and a more reasonable distribution of water and nutrients, resulting in higher yields and a more stable system. Take soybean-corn strip intercropping as an example. This combination has significantly increased crop productivity and resource utilization in many field trials, which has greatly helped China's food security and sustainable agriculture (Liu and Yang, 2024). If each strip is changed to "double-row" planting, that is, two rows of crops are planted in one strip, it can further reduce the competition between similar crops, making the yields of corn and leguminous partners more stable and higher.

3.2 Relay intercropping: sequential sowing to optimize temporal resource use

The idea of intercropping is different from that of strip intercropping. It relies on "time difference" to reduce competition. The method is very simple: plant one crop first, let it germinate, grow, and harvest first, and when it is almost finished, sow another crop. In this way, the light, water, and fertilizer consumed by the two crops are basically staggered, and they don't fight too much. Adding up the whole season, the land is more fully utilized and resources are less wasted. For example, the "relay race" mode of corn and pigeon peas is that corn comes on stage first, and pigeon peas follow up. In many areas, such relay planting can achieve higher total yields and better land utilization effects than planting only corn or only pigeon peas (Thierfelder et al., 2020).

3.3 Mixed intercropping: biodiversity enhancement and weed suppression in legume-cereal systems

Mixed intercropping refers to the direct intercropping of legumes and cereals, with wider or narrower row spacing, not requiring uniformity but seeking complementarity. With more plant species in the field, it is not easy for pests and pathogens to target them, and it is more difficult for weeds to take root, so pesticides and herbicides are naturally used less frequently. What's even better is that legumes can "catch" nitrogen from the air through nitrogen fixation and turn it into nutrients in the soil, which is equivalent to applying a layer of "nitrogen fertilizer" to cereals for free (Carlsson et al., 2020; Hossain et al., 2021). A large number of studies have shown that legume-cereal intercropping can not only improve land productivity, but also reduce yield fluctuations and make the system more resilient. For small farmers and low-input planting environments, this mixed method is a good key to stable production and increased income (Njira et al., 2024).

4 Agronomic and Environmental Benefits

4.1 Enhanced nitrogen use efficiency and soil fertility improvement

In intercropping systems, especially those involving legumes, nitrogen utilization efficiency can be significantly improved, and the soil becomes more fertile. There are symbiotic bacteria on the roots of legumes, which "pull" nitrogen from the air into the soil and supplement fertilizer in a natural way, so synthetic fertilizers can be used much less. After the nitrogen is fixed, the legumes themselves benefit first, and the crops next to them can also share the benefits. Over time, the total nitrogen reserves in the field slowly increase, and organic matter accumulates step by step (Pelzer et al., 2020; Hossain et al., 2021). Sufficient nitrogen and fertile soil, these two points work together to keep the farmland healthy in the long term and make the agricultural system more sustainable.

4.2 Increased land equivalent ratio (LER) and biomass productivity

Continuous intercropping often leads to a higher land equivalent ratio, which means that the same piece of land can produce more. Data show that intercropping can increase total energy and income by about 38%, while reducing the area of land required by 23%, with an average LER of about 1.30 (Martin-Guay et al., 2018). Long-term experiments further show that intercropping can increase grain yields by an average of 22%, with less yield fluctuations. As soil fertility increases, this advantage will continue to increase (Wang et al., 2021). Higher aboveground biomass and better nutrient utilization also prove its support for sustainable intensive production (Zhang et al., 2023).

4.3 Reduced incidence of pests and diseases through diversified planting

Intercropping is naturally labeled as "diversified", and this diversity itself is a natural pest management tool. With more plant species, the habitat in the field is richer, beneficial insects are more willing to come, the life rhythm of pests is disrupted, and less pesticides are sprayed (Huss et al., 2022). A meta-analysis pointed out that intercropping can reduce the use of pesticides for certain crops by up to 40% to 72%, while maintaining or even increasing yields and returns (Martin et al., 2024). With less chemical input, the environment is safer, and the resilience of the planting system becomes stronger.

5 Economic Implications of Legume-Based Intercropping

5.1 Yield stability and risk minimization in smallholder systems

The most obvious benefit of planting legumes together with other crops on a small plot of land is more stable yields and more risk-resistant income. With more crops, no matter how the market price and weather change, all the harvests will not be dragged down at once. A diversified layout can make the profit curve flatter, which is more reassuring than planting a single crop. Many field experiments have found that as long as the proportion of legumes is adjusted to the appropriate range, the harvest is not afraid of extreme climate such as drought. This is particularly important for small farmers who rely on the land for their livelihood (Liu et al., 2024). In addition, intercropping can also weaken the impact of price fluctuations and yield fluctuations, making the overall economic resilience even more resilient (Ha et al., 2024).

5.2 Economic returns from reduced input costs and market diversification

Leguminosae can "make their own nitrogen fertilizer", so after hybrid planting, less fertilizer is needed, saving money. The number of fertilization, spraying, and irrigation can also be reduced, and net profit and return on investment will go up (Tang et al., 2020; Mudare et al., 2022). For pairings such as corn with soybeans and wheat with peas, field data show that net income and land equivalent ratios are higher. Studies have calculated that yields can be increased by 37-43 percentage points, and carbon emissions and overall inputs can be reduced simultaneously (Sun et al., 2023). In addition, the fields can harvest a variety of agricultural products in the same season, and farmers can choose different markets to sell, with more sources of income and more freedom in selling time (Teame et al., 2023).

5.3 Labor dynamics and cost-benefit trade-offs in intercropping management

Of course, intercropping is not zero cost. With more crops, planting plans are more complicated, and row spacing and sowing order must be carefully calculated in advance. On small farms that rely mainly on manpower, arranging sowing, weeding, and topdressing will take more time than monocropping (Ahmad et al., 2019). However, in large fields with a high degree of mechanization, many links can be completed mechanically at one time. The troubles of the past are being slowly solved, and large-scale legume intercropping is becoming more and more realistic (Roberts et al., 2021). Overall, as long as you choose the right varieties, plan the rows, and adjust the sales rhythm according to the local market, the money saved on fertilizers and the extra income from selling a variety of crops can usually offset or even exceed the extra management fees (Yasin et al., 2024).

6 Case Study

6.1 Case of maize-bean intercropping in East African highlands: productivity and soil health gains

In the East African highlands, farmers often intercrop maize and beans. This practice can improve land use

efficiency and help small farmers stabilize their livelihoods. For example, research in China has found that this strip intercropping, which is mainly maize, can improve technical efficiency and make more effective use of land (Heerink et al., 2019). Although intercropping may require more labor and resources, higher land utilization can offset this effect. The benefits of long-term intercropping are also obvious: not only can grain yields increase by an average of 22%, but the organic matter and total nitrogen content in the soil will also gradually increase (Wang et al., 2021). This shows that this method not only increases yields, but also makes the soil healthier and can bring long-term benefits.

6.2 Soybean-wheat strip intercropping in China: resource efficiency and yield synergy

In China, intercropping soybeans and wheat in strips is a smarter way to use space. This method can improve resource utilization and yields (Figure 2). Data compiled by many studies show that the average land equivalent ratio (LER) of corn and soybean intercropping can reach 1.32, indicating that this method of planting is more land-saving than single planting and can also produce more (Zhang et al., 2020). Moreover, this combination uses less fertilizer under the premise of the same yield, with an average fertilizer nitrogen equivalent ratio (FNER) of 1.44, which means that the efficiency of fertilizer has been greatly improved. In addition, the time of crop sowing and harvesting is staggered, and the utilization rate of resources can continue to increase, and the overall output of the system will also increase.

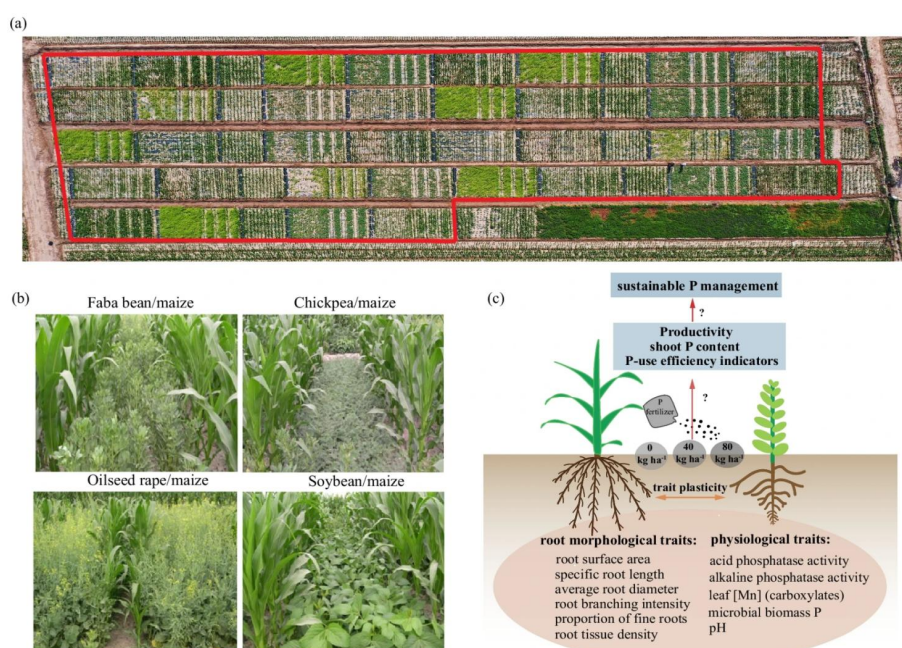


Figure 2 An aerial view of experimental plots at Baiyun Experiment Station in Wuwei city, Gansu province (a). The four intercropping combinations in the growing season (June), including faba bean/maize intercropping system, chickpea/maize intercropping system, oilseed rape/maize intercropping system, and soybean/maize intercropping system (b). Conceptual diagram of the main topic. We explored the way root traits affect productivity, shoot phosphorus (P) content and P-use efficiency indicators in intercropping with different P-application rates. We also link changes in productivity, shoot P content, and P-use efficiency indicators with sustainable P management in agroecosystems (c) (Adapted from Zhang et al., 2020)

6.3 Chickpea-mustard intercropping in India: drought resilience and economic benefits

In India, many farmers like to grow chickpeas and mustard together. This combination is not only drought-resistant, but also brings better economic returns. Studies have shown that this intercropping method not only makes the yield more stable than monoculture, but also saves arable land. Data show that after intercropping, the total energy output can be increased by 38%, the income has also increased by 33%, and the area of land used can be reduced by 23% (Martin-Guay et al., 2018). These advantages are particularly evident in areas with more droughts. Diversified intercropping methods like this can alleviate the pressure brought by climate change, make better use of limited resources, and make the income of small farmers more secure.

7 Challenges and Constraints

7.1 Complexity of management and labor requirements

Compared with planting a single crop, intercropping requires more thought. You have to think about which crops to plant, how to arrange them, when to plant and when to harvest, and all these must be planned clearly. Because different crops have different growth habits, they require different fertilizers, water, and maintenance methods, so management is more troublesome and requires more manpower (Huss et al., 2022). Farmers have to spend time learning these new skills, which is naturally more difficult. Especially for small farmers with limited resources, they still need to rely on some knowledgeable people to help them do intercropping well. Otherwise, if they rely on themselves alone, it is easy to run into problems due to lack of experience (Hossain et al., 2021).

7.2 Lack of mechanization compatibility for intercropping systems

Many agricultural machines are now designed for single cropping. Seeders and harvesters are mostly built for planting one crop. So if two crops are planted in the field at the same time, many machines will not work well (Horwith, 1985). If you want to solve this problem, you have to modify the equipment or buy customized machines, which will increase the cost a lot. For those areas that want to plant on a large scale, this mechanical incompatibility may become a major obstacle (Van Apeldoorn et al., 2021). In places that rely heavily on mechanization, intercropping promotion is indeed not easy to carry out.

7.3 Knowledge gaps and limited extension services for farmers

Many farmers don't know how to do intercropping correctly. Knowledge about which crops are suitable for combination, how to manage them, and how to deal with pests and diseases is not yet widespread. In addition, there are too few service points for technology promotion, so farmers don't know where to ask when they encounter problems (Boora et al., 2022). Many people are used to single-cropping and are reluctant to try new technologies. Without special training and guidance, it is even more impossible for them to take the initiative to try. Especially in areas dominated by traditional agriculture, the lack of targeted help makes it difficult to truly promote the intercropping model (Favarin et al., 2021).

8 Future Directions and Innovations

8.1 Integration with precision agriculture and digital farming technologies

In the future, the development of intercropping will increasingly rely on precision agriculture and digital technology. These new tools include various sensors, data analysis software and intelligent algorithms, which can help farmers better match crops, arrange planting locations, and manage resources such as water and fertilizer more finely. With these technologies, intercropping will no longer rely on experience, but will become more controllable and stable. Although these technologies are not yet fully mature and are still a little far from full application, they are already an important step towards a data-based, sustainable and diversified planting system (Leibler & Fedeli, 2024). Digital agriculture can also help farmers make decisions faster, making both small farmers and large-scale agriculture more efficient (Hallett et al., 2015).

8.2 Breeding legume varieties optimized for intercropping systems

In the past, breeding was mainly for monoculture, but in the future, if we want to do intercropping well, we have to breed some legumes that are more suitable for intercropping conditions. These varieties need to be easier to match with other crops and share resources together, and they also need to have stronger drought and disease resistance. There are already some breeding methods that can help, such as ideal breeding, plant growth simulation, and genome-assisted selection. These methods can speed up breeding and select legumes that perform better in diverse environments (Yu et al., 2022). The varieties bred in this way not only have more stable yields, but also improve the ecological function of the entire system (Van Apeldoorn et al., 2021).

8.3 Policy support and incentive mechanisms to promote diversified cropping

If leguminous intercropping is to be promoted on a large scale, policies and incentive mechanisms cannot be absent. The government and relevant institutions can encourage farmers to try diversified planting by issuing subsidies, providing technical guidance and funding scientific research projects (Ryan & Bybee-Finley, 2018). In fact, in some places, the government, enterprises and scientific research institutions have cooperated to promote

the implementation of some mixed planting models, which shows that as long as the policies keep up, the effect is still very obvious. In the future, policies can also lean more in these directions: first, reduce the difficulty for farmers to adopt new methods, second, strengthen relevant training, and third, encourage more cooperation between different fields, so that intercropping can develop faster and wider.

9 Concluding Remarks

There are many benefits to intercropping of legumes. These benefits are not only ecological, but also agronomic and economic. For example, it can make better use of land resources, make it easier for plants to absorb nitrogen and phosphorus, and make yields more stable. Land use efficiency can also be improved. At the same time, farmers will rely less on fertilizers and pesticides. In this way, not only the soil becomes healthier, but also there are more species of organisms in the fields, and the ecosystem as a whole becomes more vibrant. Moreover, farmers' incomes are often higher, or at least more stable, especially in small-scale farming systems with low investment.

More and more studies have shown that intercropping of legumes is an important sustainable agricultural method. It can maximize land use, reduce environmental damage, and help ensure food security. In the long run, it is not just as simple as increasing yields, but also makes agriculture more resilient and adaptable to changes in the face of climate change and resource constraints.

But having said that, although intercropping has many benefits, there are still many areas that can be improved. For example, how to match crops more appropriately, how to arrange field management, and how to solve the problem of mechanization mismatch all need in-depth research. In addition, new methods should be developed in breeding, digital technology, and overall system design to truly unleash the potential of intercropping. Moreover, policy support is also indispensable. The government should introduce more encouraging measures, and strengthen technology promotion and farmer training to help them learn to use these methods well. In this way, intercropping can be promoted more widely and truly solve the problems that may be faced by agriculture in the future.

Overall, leguminous intercropping is a planting method that really works well. It can make land use more efficient and make agriculture greener and longer-term. In the future, whether it is research, technological innovation, or policy, it is worth continuing to invest and support.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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