Intercropping: A Sustainable Agriculture Approach for Better Soil Health and Farm Production

Rukhsar Saleem*[1], Binish Ali[1], Adil Rehman[1], Aqeel Afzal[1], Aftab Hassan[1], Muhammad Sufhan Tahir[2] and Mishal Mukhtar[1]

[1]University of Agriculture Faisalabad, Pakistan
[2]Northwest A&F University China
*Corresponding author: rukhsarch298@gmail.com

Abstract

Intercropping is a sustainable farming practice that meets growing food demands by enhancing resource use efficiency, optimizing land utilization, and boosting yield per unit area. Better weed and insect control, decreased soil erosion, and increased soil fertility are some of the advantages of intercropping over monocropping. Diverse crops in intercropping systems utilize solar radiation better, improve water use, and balance nutrient uptake, leading to healthier soils and greater resistance to environmental stress. Legume integration in intercropping systems as maize-soybean by means of biological nitrogen fixation significantly increases soil nitrogen, enhancing soil fertility and crop yield. Additionally, by lowering its negative effects on the environment, intercropping promotes sustainable agriculture by reducing the need for chemical pesticides and fertilizers. The system's varied cropping patterns, which reduce the chance of single-crop failures, enable increased land use efficiency and yield stability over time. However, challenges like developing intercropping-compatible crop varieties and adapting mechanized farming remain. More widespread adoption is being made possible, meanwhile, by continuous advancements in plant breeding for shade-tolerant cultivars and mechanized systems for effective planting and harvesting. With careful planning and optimized planting patterns, intercropping can significantly contribute to resilient, sustainable food security amid the growing global population.

Keywords: Intercropping, Sustainable agriculture, Food security, Legume integration, Soil fertility.

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Introduction

A cropping system is a way of growing crops in a certain area over the course of a year. There are a variety of cropping systems around the world, but the system chosen for a given agro-ecological environment is preferable in terms of risk, cost, and return on investment. Growing multiple crops at once on the same piece of land (intercropping) is an appealing technique for fulfilling the needs of a rapidly expanding population (Seran & Brintha, 2010). Advancement in intercropping techniques refers to growing two or more crops on a single plot of land simultaneously in order to enhance long-term returns. For food and feed production in places where land and input resources are limited, intercropping is essential. Sustainable agriculture relies heavily on intercropping (Al-Tawaha et al., 2022).

World population is growing tremendously and hence there is a need to fulfil the foo requirements for this huge population. Possible way to increase the productivity and labor utilization per unit of land available is to use the land efficiently. Intercropping enhances the crop productivity per unit area which ensures the food surety and safety on longer terms(Seran & Brintha, 2010). Increasing crop output, improving soil fertility and productivity, and reducing soil erosion are all long-term benefits of intercropping. Intercropping offers advantage over monocropping in terms of agricultural productivity since it gives the maximum land return and land use efficiency by boosting crop output. Because it lowers the need for artificial fertilizers and pesticides, it is considered a green approach (Dowling et al., 2023).

This practice has grown popular in the tropical and rain-fed regions of the world due to the benefits of soil conservation and weed management, as well as lodging resistance, increased yield, and control of legume root parasite infections. With intercropping, we can increase crop yields per unit area by improving crop production per unit time. By reducing disease incidence, intercropping has also lowered weed density (Qamar et al., 2024).

Need for Intercropping

For all developing nations, agricultural sustainability is a never-ending challenge in order to produce food for continuously expanding requirements. Due to various human needs, area under cultivation is becoming less accessible every day. In this context, the system approach is one of the important methods for increasing agricultural output and using a systemic approach improves the effectiveness with which resources are used. To maximize the output, cropping systems must be developed based on agro climatic factors and available resources. However, according to the most recent agronomy concepts, productivity should also be measured in terms of two other dimensions, namely time and space, in addition to the productivity of individual crop.

It is always observed that the intercropping provides the crop diversification which help to achieve the potential agriculture sustainability (Andrade et al., 2020). Intercropping has various positive effects like assuring enhanced resource usage, a decrease in the number of harmful biotic agents, increased resource conservation and soil health, as well as increased production and sustainable system output (Maitra et al., 2023). As two or more crops are grown together on the same piece of land in an intercropping system, which makes efficient use of the soil's nutrients, moisture, atmospheric CO_2, and sunlight. An intercropping system has good benefits on soil health, resource conservation, and run-off because it reduces soil erosion and nutrient loss (Gitari et al., 2019) (Fig. 1).

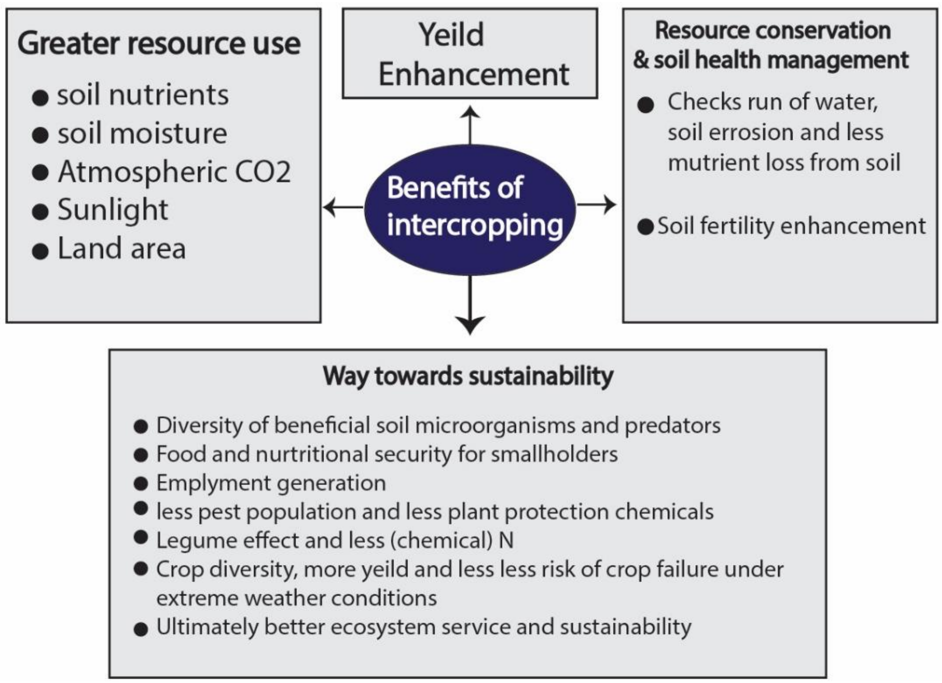

Fig. 1: Benefits of Intercropping: This image demonstrates greater use of resources and conservation, soil health management and suggest way towards to sustainability (Maitra et al., 2023)

The Future of Global Agriculture: Challenges and Pathways to Sustainable Food Security

Agriculture is the world's largest food producer and a key driver of economic development. According to the United Nations' Food and Agriculture Organization (Joint), global food demand must increase by 70% by 2050 in order to meet current levels (Mishenin et al., 2021). 500 million people are malnourished and over 821 million go hungry despite current production being sufficient to feed the whole world's population. When it comes to the goal of eradicating hunger, this population growth provides a significant obstacle. The global demand for food is influenced by these forecasts for the next few years. Increased crop yields and lower resource consumption are therefore necessary for food production; as current resources are not sufficient. In 2050, the world population may reach to 9.8 billion and hence annual cereal production should also increase to 3 billion tonnes (Okolie et al., 2022). The rise in yields will have a direct impact on the amount of cereal available. Improvement in cultivation practices, structural changes toward larger farms, and the ability to adapt technology are all necessary to meet this demand for increased production capacity.There is a projected increase in the population from 6.8 billion in 2010 to 9.7 billion in 2050, as well as a corresponding increase in the food supply per capita from 1.86 kg to 2.08 kg per day. A total food supply growth of 60 percent is expected from 2006 to 2050, according to Alexandratos and Bruinsma (Conijn et al., 2018).

As the world's population continues to grow, so does the need for a solution to the problem of food security. The world's population is expected to grow by 1.7 billion people between now and 2050, putting an increasing amount of strain on the limited resources that may be used to produce our food (Wang, 2022).

Challenges in World's Agricultural Sector: Pathways to Sustainable Growth and Productivity

Our economy relies heavily on the agricultural sector. World's agricultural development is facing several difficulties. Due to a variety of circumstances, per-acre yield is significantly lower than that of other industrialized nations. With its reliance on tillage, conventional agriculture raises production costs, damages soil quality, and contributes to global warming. Due to the challenges of traditional agriculture, a transition to conservation agriculture (CA) has emerged as the most practical solution (Soni et al., 2022).

By 2050, as animal welfare improves, we can expect a shift in consumer preferences toward animal-derived foods. Land use will also be drastically altered as a result of the increased need for feed crops. New plant types and improved agricultural practices will have a role in determining how much arable land is needed in the future (Fróna et al., 2021). Modern technologies cannot be used in agriculture because land holdings have been so extensively subdivided and fragmented. Similarly, the smaller area had a lower grain output, which was insufficient to meet our food needs. The low yield per hectare of nearly every major crop is the most important problem in agriculture. The adoption of modern technology and modern frame methods like intercropping in other nations around the world, on the other hand, has led to increased yields per hectare (Abbas et al., 2022).

Agricultural mechanization is increasing in all over the world, but in most areas, old implements are still used for agricultural production. Traditional manufacturing techniques cannot increase output to international standards. In under developing countries, the supply of modern inputs such as high yielding variety seeds, chemical fertilizers, pesticides, mechanized machinery, and so on is not only expensive, but also insufficient and irregular. Similarly, cropping intensity refers to the number of crops grown on a given plot of land in a given year. Cropping intensity is low in our current stage of development when compared to advanced countries. In Pakistan, cultivable land under double or multiple cropping systems is insufficient (Qamar et al., 2024).

Constant cultivation of one or two crops depletes the soil's fertility. Proper crop rotation and intercropping are required to restore fertility. Mono-cropping can intensify these environmental problems due to the presence of a large bare soil surface, low soil fertility status, destroys soil health, with added economic threats owing to the low resilience to variability in prices, markets, climate and pests and diseases due to the dependence on a single crop (Morugán-Coronado et al., 2022) (Figure 2). . Pests and insects frequently attack agricultural crops such as cotton, sugarcane, tobacco, wheat, and rice. Pests and plant diseases reduce agricultural productivity.

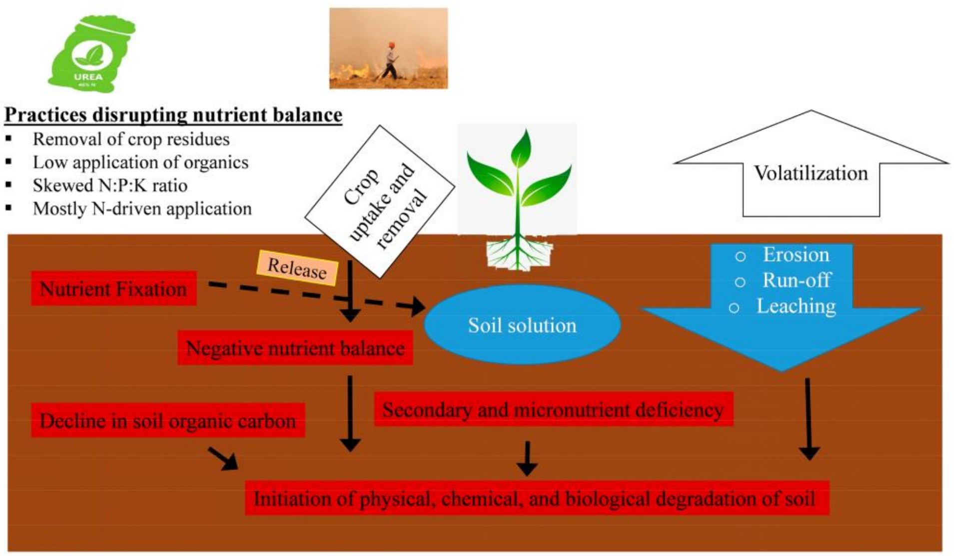

Fig. 2: A clear differentiation of mono cropping which increase seed borne diseases and soil erosion and decrease nutrient efficiency, water use efficiency, biodiversity, soil functional microorganisms while on the other hand diversified cropping system works opposite to monocropping system (Yang et al., 2022)

Under developing countries' average crop yield is very low when compared to the production levels of the world's advanced nations. Continuous improvement in agricultural growth research is required to increase the potential of agricultural production. Most farmers are poor and have low levels of income. In many countries, agriculture credit is not widely available. So a farmer is born in debt, grows in debt, and dies in debt. It means that the financial situation of farmers is precarious.

Intercropping Perspective and Opportunities

Sustainable agricultural strategies that boost crop productivity without using excessive fertilizer or increasing cropland are vital if we are to maintain our future food supply and air quality. Intercropping legumes and non-legume crops is a common practice among farmers. Plants use symbiotic rhizobia bacteria in their root nodules to execute biological nitrogen fixation (BNF), which involves converting atmospheric nitrogen (N_2) gas to ammonium (NH^{4+}) or organic nitrogen for plant uptake (Soumare et al., 2020). Legumes and other crops can compete for soil nutrients through intercropping, which could limit the legumes' nutrient supply and speed up the BNF process for the symbiotic bacteria (Lai et al., 2022).

Conventional farming's use of fertilizer is particularly harmful to the environment because it damages water and soil quality and disturbs the global nitrogen (N) cycle by increasing emissions of reactive nitrogen gases including ammonia (NH_3) and nitrogen oxides (NO and N_2O) and this might rise by 45-73% by 2050 to meet global demand (Fung, 2019).

Effect on Crop Growth

Maize soybean intercropping has boosted the plant's overall height and stem, as well as the amount of chlorophyll, feed, and grain output (Nasar et al., 2020). Maize-soybean intercropping in various spatial patterns results in various light and shadow situations above the soybean canopy, which has a direct impact on soybean leaf structure (anatomic) and photosynthesis fluorescence properties. As a result of the shade from the higher maize plant, the lower soybean plant is deprived of both the amount and quality of light. This could lead to changes in the soybean crop's internode length, plant height, leaf diameter, and branching, among other things (Xu et al., 2024).

Stem elongation has been shown as a method used by plants to boost their solar energy absorption. This decreases the soybean stem's diameter and its ability to withstand lodging in the long run. These constraints on soybeans are linked to the development of the corn canopy. In addition, soybean stem circumference shrinks under the shade of maize, making it less prone to lodging (Wang et al., 2023).

Water use Efficiency

Plant growth is dependent on the availability of water in the cropping system. When water efficiency is increased in intercropping, other resources are used more frequently. Because of its early high leaf area index and greater leaf area, intercropping has been demonstrated to save water (Begam et al., 2020). Water loss is reduced, absorption is increased, and transpiration is boosted by a variety of root systems in the soil, resulting in a cooler microclimate than the surroundings. Cereal-legume crops use water more efficiently than monocropping crops (Amanullah et al., 2021).

A study found that intercropping increased soil water conservation and reduced soil run-off, while also allowing them to make better use of the water they have on hand (Raza et al., 2021). This led to an overall increase in crop yield, as well as an increase in yield per unit of water supplied and the yield of crops planted the following year (Gitari et al., 2019).

Nutrient use Efficiency

It is common for the nitrogen utilization efficiency of individual crops in an intercrop to be lower than that of their solitary crops. An intercropping system has a superior cumulative nutrient use efficiency than either of the sole crops in most circumstances (Fan et al., 2020). Improved nutrient uptake and balanced nutrient usage (Raza et al., 2021).

Solar Radiation use Efficiency

Intercropping offers the advantage of capturing and utilizing more solar radiation than monocropping (Abbas et al., 2022; Pierre et al., 2023). It is possible to boost productivity per unit incident radiation if a new intercropping system is adopted that increases solar radiation interception or has a more efficient radiation utilization. A higher proportion of biomass was partitioned to yield as a result of improved radiation energy utilization (Sarangi et al., 2020; Sgarbossa et al., 2024).

Increase Soil Fertility through Nutrient Acquisition

Soil advantages from intercropping cereal (maize) and legume (soybean) crops can be substantially increase the coil fertility through N and P uptake (Tang et al., 2023). Increased forage yields and improved soil health can be achieved by intercropping silage maize and feed soybean. It is less expensive to fertilize soil with atmospheric N when legumes are used as they use the phenomena of biological nitrogen fixation as shown in (Figure 3) (Phiri et al., 2014). When non-fixing (maize)f crops are interspersed with N-fixing (soybean) crops, yield and productivity are reportedly increased. Soybean fixes atmospheric N instead of competing with maize for soil N when N fertilizer is not available (Brintha & Seran, 2012).

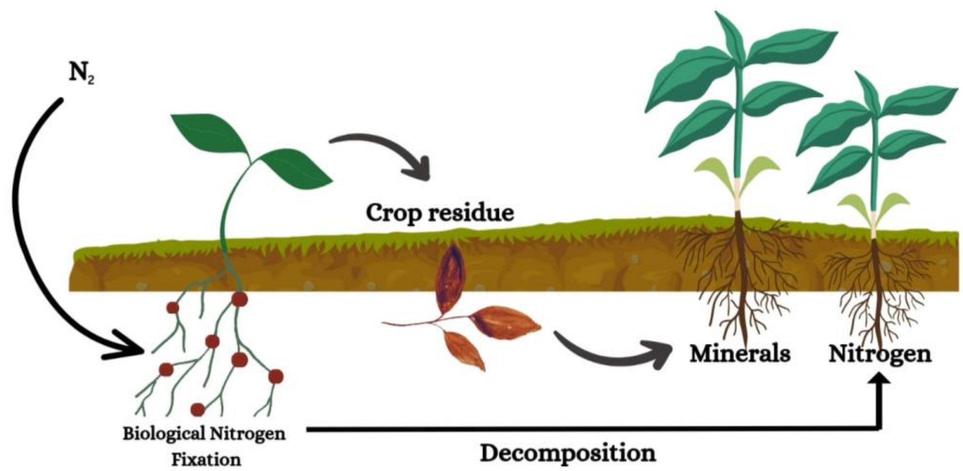

Fig. 3: This image represents the whole mechanism how cereal-legume intercropping enhance soil fertility by biological nitrogen fixation in rhizosphere then crop residue decompose in soil and release minerals in soil and maintain soil health (Thies & Grossman, 2023)

Weed Management

Because intercropping ensures a greater utilization of resources, a lower population of hazardous organisms, more resource conservation and soil health, and a higher level of production, intercropping is beneficial in many ways increased competitiveness, physical dominance, space occupation, and allelopathic effects are all benefits of intercropping. Due to biochemical effects, intercropping allelopathic crops with other crops may increase weed control in the main crop (Maitra et al., 2023).

Weed control was excellent when intercropping was combined with optimal row spacing and hand weeding. Intercropping pea in wheat crop at various ratios dramatically reduced weed density and fresh and dry biomasses in a recent study from Pakistan (Jabran et al., 2020). In general, intercropping is better in weed control than monocropping, although its efficiency varies depending on its ability to invade weed resources or reduce weed development through allelopathy.

Pest Management

A pest's capacity to recognize its host plant is compromised when it is interplanted with two other crops on the same piece of land. Intercropping can also be utilized to reduce pesticide consumption in crops. For example, pests and diseases are minimized when tomato is intercropped with maize. Weed growth is significantly reduced in intercropping systems compared to monocultures. Reduced weed populations and biomass output can be achieved through intercropping. So, in terms of weed management, Intercrops may be superior to solitary crops (Maitra et al., 2019)

More crops can be produced with less weed development if intercrops can usurp weed resources or suppress weed growth through allelopathy more effectively than solitary crops. However, if intercrops employ resources that weeds cannot access or convert resources to harvestable material more efficiently than sole crops, they may provide yield improvements without reducing weed growth (DINSA & Zeleke, 2020).

Soybean red crown rot disease incidence and severity index decreased as a result of pest, disease, and weed management in intercropping. Furthermore, the severity of disease was dramatically reduced when soybeans were grown adjacent to maize. Intercropping with maize can considerably minimize or even eliminate the occurrence and development of red crown rot in soybean growth when the intercropping planting distance is taken into account (Chang et al., 2020).

Erosion Control

Intercropping protects soil from desiccation and erosion by providing year-round or at the very least long-term ground cover than monocropping. Surface pores can be clogged by rain, preventing water from reaching the soil and causing surface erosion. Protecting the soil from compaction is a primary goal of intercropping with legumes. Smaller leguminous crops, such as soybeans, benefit from the wind-blocking effect of taller maize fields, which reduce wind speed and avoid saltation and wind erosion (Gebru, 2015).

Soil depletion can be better protected when cowpea is intercropped with maize because of its ability to disguise the soil surface and, when intercropped with maize, better protect the soil from erosion. Intercropping maize and legumes, the study found, is an effective way to reduce soil erosion (Dwivedi et al., 2015).

Effect on Soil Fertility

As more than one crop is grown in the intercropping system, above-ground diversity is also more obvious. Additionally, different crop mixtures boost the population of various arthropods, insects, and birds. When cowpea was taken into account as a legume crop in intercropping, discovered a greater diversity of pollinators (Josephrajkumar et al., 2022). In addition, variety in microorganisms increases below-ground diversity. Rhizobium population increases in legumes when they are considered a component crop in intercropping, together with other advantageous microorganisms including *Pseudomonas* spp., (Chamkhi et al., 2022) *Alphaproteobacteria*, *Betaproteo* bacteria, and *cyanobacteria* which increase the soil health, as microbial count take as an indicator of soil. In the end, all of these result in a healthy environment. Additionally, intercropping reduces the number of hazardous soil microorganisms (Wang et al., 2020).

Future Prospects of Intercropping: Innovations and Strategies for Enhanced Agricultural Productivity

Improved Genetically Modified Breeds

Soybeans benefit from the shade provided by maize in an intercropping arrangement. Due to stem elongation and lodging, many soybean cultivars are less productive in the shadow. Shade-sensitive soybean varieties in an intercropping system involving corn and soybean show stem elongation and lodging, which have a direct effect on soybean yield, according to various studies (Wang et al., 2023).

Because of their shade tolerance, a growing number of soybean land races have been discovered. Several land races are being utilized to breed cultivars for intercropping schemes in different parts of the world. Intercropped soybean yields can be improved by using semi-dwarf but high-yielding maize hybrids (Blessing et al., 2022). To lessen the biomass and leaf area index discrepancies across intercropping systems, semi-dwarf cultivars might be used. Compact planting methods increase the density of strip-crop intercropping (Zhao et al., 2023).

Improved Mechanized Systems

A wide range of intercropping practices can be accommodated by agricultural equipment for planting, fertilizing, and harvesting. Seed and fertilizer drills for this systems like maize-soybean strips in the field could be useful for future research. When agricultural machinery is specifically constructed for this manner, labour productivity rises dramatically. In China and other emerging countries, our new intercropping approach has the potential to greatly enhance soybean yields (DU et al., 2018).

Intercropping as System Productivity

Intercropping can be improved by controlling the planting density, which is determined by the planting ratio and distance. Designing the planting pattern in narrow and broad rows, such that maize plants can grow in narrow rows and soybean plants in wide rows, all while ensuring that soybean plants receive ample light for optimal growth and development, could be accomplished (Sreekanta et al., 2024). Increasing soybean seed output in an intercropping system might be achieved by constructing an efficient intercropping planting layout with a maximum shade density (Wang et al., 2023) Increased soil fertility, improved resource efficiency, and improved soil conservation are just a few of the advantages of including legumes into the mix. It also minimizes the need for plant-protection pesticides because of intercropping's ability to control pests, diseases and weeds.

Conclusion

To sum up, intercropping is an ancient agricultural practice that has recently gained popularity as a sustainable alternative to modern-day monoculture farming. This practice improves soil health by promoting nutrient cycling near each other, an added benefit is that the likelihood of topsoil depletion will be reduced by this way of growing multiple crops together. This also enhances total crop production, as plants complement each other in utilizing sunlight, water, and nutrients efficiently. Secondly, intercropping also reduces the application of chemical inputs like fertilizers and pesticides since plant diversity will tackle pests and suppress weeds. Such practices result in healthier ecosystems, which can save farmers money. Soil is also well protected from wind and water erosion, as intercropping offers constant cover with crops. It ensures long-term agronomic sustainability by optimizing the use of resources and improving biodiversity. It offers a responsive & sustainable method to satisfy the increase in worldwide demand for nutrition whilst reducing climate change problems. Intercropping is one of the main pillars of an ecological approach to farming thereby contributing to a profitable farm system and plays a key role in the transition towards an ecologically sound and food secure future.

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