

Technology-integrated intercropping for optimizing crop yield and sustainability in Pakistan

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ABSTRACT

Intercropping is an effective practice for enhancing crop productivity, resource efficiency, and pest control, yet its full potential in Pakistan and other developing countries remains underutilized. This review emphasizes how modern technologies—such as precision agriculture, remote sensing, the Internet of Things (IoT), artificial intelligence (AI), and advanced sensing tools—can strengthen intercropping systems by improving resource management, pest and weed control, and crop monitoring. Technologies such as UAVs, GPS/GIS, variable-rate applications, and AI-driven decision-support systems enable farmers to manage field variability, optimize water and nutrient use, and more accurately predict pest outbreaks. AI also supports climate-smart agriculture by forecasting weather, enhancing crop resilience, and increasing global food security. Despite these benefits, adoption of these technologies faces challenges including high costs, limited technical skills, data processing issues, privacy concerns, and energy demands of big data systems. This review highlights key research gaps, especially the limited integration of precision agriculture with IPM and intercropping, and stresses the need for affordable, scalable, and farmer-friendly technological solutions. Overall, combining intercropping with emerging technologies offers a promising path toward sustainable, resilient, and productive agriculture in Pakistan and similar regions.

INTRODUCTION

Pakistan is an agricultural country; the main products are categorized into major crops such as wheat, rice, cotton, sugarcane, and maize, and minor crops such as fruits and vegetables, including potatoes, onions, chilies, tomatoes, mangoes, citrus fruits, and dates (Ministry of National Food Security & Research, 2023). Exports of up to 50 percent and sustenance of up to 70 percent of the population are directly linked to Pakistan's agriculture. Agriculture supports the country's economy, food, and industry (Awan and Aslam 2015), and is considered the largest sector of Pakistan's economy. But due to recent challenges in agriculture, some authors now refer to it as the second-largest sector rather than the first. These problems have reduced productivity, thereby jeopardizing the country's food security. Firstly, the mean temperature in Pakistan is increasing, disrupting rainfall patterns and leading to water scarcity or floods. The situation is even worse than in other countries because this upward temperature trend exceeds the global average rate of warming. Pakistan receives more than 90% of its rainfall during summer, including monsoon

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rainfall, but this is changing due to climate change, which is altering cultivation practices (Farid et al. 2022). Secondly, extensive intensification of major crops in Pakistan has depleted soils of macro- and micro-nutrients, including organic matter, leading to soil degradation, as evidenced by Pakistan's fertile soil layer at 15 cm compared to 10 cm in other countries (Khan et al. 2022). Lastly, insect pests also reduce overall yield by either consuming tissues or sucking plant sap, leading to losses of up to 20% in major and potential crops cultivated in Pakistan, including wheat, maize, canola, and soybean, among others (Oerke 2006; Rehman et al. 2015).

Moreover, instead of rectifying these problems or eliminating their root causes, we are more dependent than ever on monocrops, promoted in South Asia, including Pakistan, during the green revolution to sustain productivity and food security. Monocropping has been shown to cause long-term productivity decline and is now being extensively investigated for poor yields. This downward trend is attributed to multiple factors, including pest outbreaks driven by abundant foraging resources and mismanagement of pesticide applications, which allow pests to become stronger and more resistant to chemical control (Ali and Byerlee 2002). Intercropping has been widely advocated to counter these limitations of monocropping. Through efficient use of resources, intercropping has been proven to increase productivity per unit area. This, in turn, leads to biomass stability as crops in diverse systems compensate for one another, support soil fertility, and protect against pests, weeds, and diseases. Intercropping in developing countries is also lucrative for farmers, offering economic benefits and a higher land equivalent ratio (LER). The success of intercropping results from the complementarity between primary and secondary crops in canopy, stem, and root structure, and in flowering and maturity periods, to ensure maximum utilization of available resources (Aziz et al. 2015).

In Pakistan, the dominant intercropping pattern is wheat-canola, while maize-soybean intercropping is also emerging, with proven benefits reported from different parts of the world. For example, a 2001-2003 study from Manitoba, Canada, reported that wheat-canola intercropping not only suppressed weeds but also produced a land equivalent ratio (LER) of greater than one irrespective of herbicide application, which shows improved yield even with chemical applications, which is the core objective of intercropping (Szumigalski and Van Acker 2005). Similar results were also reported by authors from Pakistan, who reported improved yield, with LER values > 1 (Ali, Malik, and Cheema 2000). Similarly, maize-soybean systems have been shown to improve yields compared to monocrops. Results of a case study from Punjab, Pakistan, showed that maize-soybean intercropping improved LAI (leaf area index) by 19 percent, TDM (total dry mass) by 15 percent, and yield by 21 percent compared to solo crops with LER of more than one and improved water use efficiency (Raza et al. 2021). In addition to LAI, TDM, yield, LER, and water use efficiency, maize-soybean intercropping has also been shown to improve radiation use efficiency in Pakistan, linked to enhanced photosynthesis and therefore, yield (Raza et al. 2022).

Here, we argue that incorporating technology into agriculture can improve already promising intercropping combinations across different indicators of intercropping benefits. This is particularly important for developing countries like Pakistan, both for small-scale and progressive farming. The integration of technology must align with the local environment to achieve optimal outcomes. This review

illustrates the use of technology in agriculture and the advantages of integrating technology in Pakistan and South Asia.

INTEGRATION OF TECHNOLOGY IN INTERCROPPING

The best depiction of the integration of technology into agriculture, or conventional agricultural practices such as intercropping, is precision agriculture (PA). Field and crop variability is the most critical hindrance to achieving higher yields in agriculture. Precision agriculture uses data to manage variability. Farmers can predict practices based on information related to soil, crop and environment. PA enables the effective use of farm resources for efficient, sustainable production through real-time data. An essential component of PA is IoT (Internet of Things). IoT sensors are set up to monitor field and crop conditions for optimal resource allocation through VRT (variable rate technology). Similarly, AI-based DSS (decision support systems) and software applications are being used to monitor pests and weather. Below is an account of how technology can improve aspects of conventional agriculture, such as intercropping (Saha et al. 2025).

Resource Management

The use of intelligence and communication technologies (ICTs) and e-agriculture can boost productivity by allowing more efficient use of resources than conventional intercropping. For example, automated drip irrigation, which receives input from multiple sensors dedicated to various environmental variables and factors, can prevent water loss, which is also critical given that the water level in Pakistan is declining at an alarming rate. Such technology-informed use of resources is termed precision agriculture (Shafique, Ali, and Salman 2019). Conventionally, intercrops like wheat-canola and maize-soy bean in developing countries like Pakistan are irrigated on a whole field basis at regular intervals based on prior knowledge. At the same time, some farmers consider soil moisture, crop needs, climate, and weather conditions while applying irrigation. Unfortunately, field variability is largely ignored. Remote sensing can solve this problem by allowing variable irrigation in fields, preventing water loss. Sensors can reduce water application by 25 percent (Kebe et al. 2023). Remote sensing has further improved precision agriculture by enabling more accurate predictions of water and nutrient requirements. Other technologies aimed at the precise utilization of resources include Global Positioning and Information Systems (GPS and GIS) and artificial intelligence (AI) models, including machine learning and neural networks. These technologies generate large volumes of resolution data, which are processed using Big Data analysis and cloud computing across multiple servers (Sishodia, Ray, and Singh 2020).

Intercropping is usually resource-intensive; addition of resources is generally a tradeoff for higher yield and hence higher market value. But this fragile balance can be disturbed when appropriate nutrients are not applied in appropriate quantities and of proper quality. Nutrient requirements vary across crops, and across space and time. Remote sensing-based vegetation indices can help locate areas of high and low resource availability for proper application. For small-scale intercropping, tractor-mounted sensors can also be used (Ali et al. 2017). Similarly, AI-driven remote sensing-based seeding is being used to optimize

plant growth and land use. Variable rate technology or VRT-enabled nutrient applications increased soybean production by eighteen percent. This technology enables precise applications tailored to the need (Kebe et al. 2023).

Pest management

Similarly, environmental variables can be correlated with pests' population dynamics to predict outbreaks. This can play a key role in the success of intercropping. Likewise, satellite surveillance can be used to monitor the delicate balance of productivity, pests, and diseases in intercropping settings. The Internet of Things, or IoT, has been gaining popularity in agriculture. It allows integration of multiple technologies for a single output. For example, numerous factors can be integrated to predict when to harvest the crop for optimal quality or when to apply control measures for pests. Integration enables precise decision-making to improve yields. This integration is based on wireless sensor networks (WSNs), enabling real-time data transmission without lag, delay, or distortion for optimal resource allocation in intercropping (Shafique, Ali, and Salman 2019). For pest outbreak predictions, as discussed earlier, IoT can be used to feed environmental inputs such as humidity, temperature, wind, solar duration, and precipitation into deep learning neural networks for reliable outcomes. Accuracy of such models gets improved as the model is trained. Studies have suggested an accuracy of up to 94 % with high precision. Conventional intercropping techniques lack real-time data-backed interventions, hence monocultures still prevail when intercrops cannot provide desired outcomes (Saleem et al. 2023). IPM and PA can be integrated to further solve pest problems in intercropping. For example, in Iowa, USA, this integration enhanced corn yields by 20% and reduced pesticide use by 30% (Kebe et al. 2023).

Weed management

Weed management is complicated in intercropped fields, as crop structures and intercrop patterns can restrict weed movement. Furthermore, if herbicide is to be applied, the choice of chemical can be challenging, as the herbicide should not damage the intercropped plants. Remote sensing also comes into play here, with UAVs as the most appropriate tools for detecting and mapping weeds at centimeter resolution, achieving up to 90% accuracy (Huang et al. 2020; Huang et al. 2018). Similarly, physical and laser-based weeders are being employed that use GPS coordinates and image recognition to remove weeds.

Crop monitoring

LAI and yield are essential indicators of intercrop success. Conventional methods for accessing these estimates do not account for the remarkable variability in LAI and biomass. Remote sensing is being used in row intercrops to assess these indicators accurately. This is important for evaluating crop health and the response of intercrops to management and climate (Peng et al. 2019).

EMERGING TECHNOLOGIES AND INTERCROPPING

New satellites are being launched for remote sensing and land monitoring. Recently, in 2025, the NASA-ISRO Synthetic Aperture Radar (NISAR) satellite was launched. Its radar has two frequencies. These frequencies can penetrate cloud cover and plant canopies, providing detailed, high-resolution information twice every 12 days (Bradbury et al. 2025). This information will be helpful for farmers in the optimal allocation of resources. In the face of climate change, crop cultivation may explore non-traditional areas, which may require UGVs (unmanned ground vehicles) and other robotic systems to perform different aspects of cultivation. For example, robotic systems by ecoRobotix perform weeding using AI with a precision of 6cm by 6cm. As space for cultural practices is usually an issue in intercropping, this system can drastically reduce weeds and improve productivity.

Artificial intelligence (AI) is becoming an essential tool for climate-smart agriculture, helping farmers deal with changing weather and reduce climate-related risks. AI can analyze vast amounts of weather data, satellite images, and climate records to predict droughts, heavy rain, or temperature shifts. These early warnings help farmers adjust planting dates, irrigation, and other practices before damage occurs. AI also supports crop resilience in drought-prone areas by identifying drought-tolerant varieties and guiding precision irrigation based on real-time soil moisture and climate forecasts, improving both yields and water efficiency. Beyond climate adaptation, AI strengthens global food security by boosting productivity. Machine learning tools analyze soil, weather, and crop performance to provide farmers with practical recommendations that increase yields while reducing the waste of water, fertilizers, and pesticides. This is especially valuable in regions with food shortages. International organizations such as the FAO and NGOs are promoting AI-based farming through training programs and climate-smart agriculture initiatives, helping farmers worldwide adopt these technologies. Overall, AI improves productivity, resilience, and sustainability, making it a powerful tool for securing the future of global food systems.

CHALLENGES AND SOLUTIONS IN ADOPTING TECHNOLOGY-BASED INTERCROPPING

Although satellite data can be freely available on the web, it still requires knowledge and experience with the data itself and the software used to process it. For example, image processing is necessary to evaluate such data. Another problem with freely acquired data is that its temporal resolution can be limited, and its spatial resolution can be broader. This can hamper precise analysis and interpretation. Generally, farmers don't tend to purchase high-resolution data, even if they can afford it. However, small farmers can leverage UAVs to capture low-cost, high-resolution images (Candiago et al. 2015). However, the use of UAVs also requires specialized data analysis software and licensed operators (e.g., drone operators) (Ali et al. 2017). Similarly, UAV sensors and image analysis are costly and challenging, at least for someone new to the field (Khanal et al. 2018).

Farmers face many challenges when using deep learning to predict crop yields. Different regions have different soils, climates, and farming methods. So, it's hard to make one model that works everywhere. Good data is critical, but often the information about soil, weather, or plant growth is incomplete or noisy.

This makes predictions less accurate. Deep learning models can be powerful, but they require substantial time and computational resources to train, and more complex models don't always yield better results. Satellite images and sensor data help monitor crops, but combining data from many sources is tricky. Farmers also worry about who owns and controls their data. So, clear rules and trust are needed. Finally, big data centers that run these models use a lot of energy, which can harm the environment. To improve crop prediction, we need better data, fair data-sharing rules, and more energy-efficient technology to make farming more sustainable and reliable (Saha et al. 2025).

To improve crop prediction, future models will use more complex structures that integrate satellite data with farm data and historical crop records. This means mixing spatial data (such as soil measurements) with historical data (such as crop rotations) and multisensory inputs, along with satellite-based plant growth patterns. These improvements could lead to cloud services that provide accurate global crop maps. Transfer learning will also help by using models trained on large datasets and adapting them to new areas, reducing the need for local data collection. However, resolution bias is a challenge because satellite pixels sometimes include non-crop features like ponds or canals, especially in hilly regions. To fix this, unbiased methods must be used to adjust crop-area estimates so that predictions match real conditions.

SUMMARY OF TECHNOLOGICAL OPPORTUNITIES IN INTERCROPPING SYSTEMS

The environmental benefits of intercropping, including enhanced resource-use efficiency, weed suppression, improved soil fertility, reduced pest pressure, and greater resilience to climatic stresses, can be substantially amplified through digital agriculture technologies. Precision irrigation, UAV-based monitoring, AI-driven decision-support systems, remote sensing, and IoT-enabled sensing networks improve the management of intercrop variability while reducing inputs and environmental impacts. Summaries of the major intercropping systems and associated technological opportunities, and practical implementation priorities for Pakistan are given below (Tables 1 and 2).

Table 1: Major Intercropping Systems, Environmental Benefits, and Technology Add-on Value.

Intercropping System	Environmental Benefits	Evidence	Technology Add-on Value
Wheat-Canola	Weed suppression, improved land productivity, better resource utilization	LER > 1 reported in Pakistan and Canada	UAV-based weed detection, GPS/GIS-guided nutrient management, AI decision support for irrigation and fertilizer scheduling
Maize-Soybean	Improved water-use efficiency, radiation-use efficiency, biomass accumulation, yield enhancement	Increased LAI, TDM, yield, and water-use efficiency in Pakistan	IoT soil-moisture sensors, variable-rate irrigation, remote sensing for crop monitoring, AI-based yield prediction
Legume-Based Intercropping (general)	Biological nitrogen contribution, reduced fertilizer dependence, improved soil fertility	Discussed as a mechanism underlying intercrop complementarity	Variable-rate nutrient application, sensor-based nutrient monitoring
Technology-Enabled Intercropping Systems	Reduced pesticide and water use, improved resource-use efficiency, climate resilience	Precision agriculture and IPM integration improved yields and reduced pesticide use	AI, UAVs, remote sensing, IoT, DSS platforms, automated irrigation systems

Table 2: *Recommendations for Technology-Based Intercropping in Pakistan*

Recommendation	Expected Impact	Cost	Priority
Promote IoT-enabled irrigation systems in intercropped farms	High water savings and improved water-use efficiency	Medium	High
Expand UAV-based crop and weed monitoring services through cooperatives	Better weed management and timely interventions	Medium to High	High
Develop AI-based pest forecasting systems integrated with IPM	Reduced pesticide use and crop losses	Medium	High
Provide government subsidies for precision agriculture equipment	Accelerates technology adoption among smallholders	High	High
Establish farmer training and extension programmes on digital agriculture	Improve technical capacity and adoption rates	Low to Medium	Very High
Develop local data-sharing and privacy regulations	Builds trust and supports AI adoption	Low	Medium
Encourage public-private partnerships for affordable technology access	Improves scalability and reduces farmer costs	Medium	High

Support research on precision agriculture-intercropping integration under Pakistani conditions	Generates locally validated solutions	Medium	Very High
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CONCLUSION

The integration of modern technologies with intercropping offers a powerful way to address Pakistan's agricultural challenges, including climate stress, soil degradation, and rising pest pressure. Tools such as IoT sensors, UAVs, remote sensing, and AI-based predictive models provide farmers with real-time information to make better decisions on irrigation, fertilization, pest control, and crop health. These innovations make resource use more efficient, improve yields, and increase system stability compared with conventional practices. However, widespread adoption is limited by high costs, technical complexity, data privacy concerns, and the need for skilled operators. Future efforts should focus on developing low-cost, easy-to-use technologies and on creating policies that support farmers through training, subsidies, and data protection regulations. Stronger integration of precision agriculture with IPM and intercropping, supported by AI and climate-smart tools, will be essential for building resilient farming systems. By overcoming these barriers, Pakistan and other developing countries can achieve sustainable productivity gains and improved food security.

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