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COTTON-BASED INTERCROPPING: A CLIMATE-SMART APPROACH FOR FIBER AND FOOD SECURITY

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ABSTRACT

Intercropping, a farming technique that involves growing two or more crops together, has emerged as a potential solution for climate change and global warming. It holds particular importance in subsistence or resource-limited agricultural systems operating on the fringes of modern intensive agriculture. Intercropping offers the opportunity for genuine yield gains without additional inputs and can contribute to achieving "sustainable intensification" by enhancing yield stability while reducing resource requirements. In developing countries, the cultivation of cotton is declining due to the impact of changing climates. However, cotton-based intercropping presents a promising solution to address this issue. Implementing intercropping systems with cotton as a central crop, not only can increase yield but can also enhance stability in erratic climatic conditions. The primary advantage of growing two or more crops together in an intercropping system is the increase in productivity per unit of land. This farming practice optimizes the utilization of environmental resources, aiming to maximize crop production within a given area and timeframe. Intercropping allows for the inclusion of various crops such as cereals, legumes, and vegetables alongside the standing cotton crop. Each crop group brings diverse benefits and higher monetary returns. This review shows how various crops can be intercropped with cotton and the overall efficiency of cotton-based intercropping systems under climate change.

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INTRODUCTION

Agriculture in the 21st century is facing multiple challenges and among them, the most imperative is to produce more food and fiber to a growing population. Many species of crop plants are very sensitive to increasing temperature. The changes in climatic events (temperature, precipitation etc.) can affect agriculture productivity (Abbas, 2020). On the other hand, the increase in the world's population is putting stress on the agriculture sector to increase food production. The predictions reveal that nourishing the 9.1 billion people in 2050 would need an increase in overall food production by 70% and 4 to 5 folds production of fibre (FAO, 2009; Ray et al. 2013; Mall et al. 2017). Many reports show that the yields of crops are not increasing fast enough to sustain the expected demand in 2050, and the world will face a shortage of food and food disasters (Ray et al. 2013). Cotton productivity has to be significantly increased, ensuring its sustainable development and environmental compatibility for the benefit of future generations. There is need to adopt practices that balance productivity with environmental preservation. To achieve this goal, it is essential to embrace sustainable agricultural approaches. These methods prioritize maximizing productivity while minimizing negative environmental impacts. Among the other practices to increase crops yield, intercropping is a sustainable farming practice that increases crops production by reducing the chances of crop failure owing to better use of resources such as nutrients, water and sunlight (Lulie, 2017; Hassen et al. 2017). In intercropping, two or more crops are grown together and coexist for a certain period. Intercropping addresses many key problems of agricultural farming systems such as low yield, soil degradation, pest and pathogen infestation and environmental deterioration (Amin et al. 2018; Wang et al. 2022; Xie et al. 2022). In intercropping, both main crop and component crop use resources like nutrients, space, water light etc.) more efficiently than single crop, and consequently, fewer resources are available for weeds and pests' utilization (Mohler and Johnson, 2009; Zaefarian and Rezvani, 2016). Intercropping also decreases the risks of total crop failure and reduces insect pest infestation and also weeds infestation significantly by shading them (Zaefarian and Rezvani, 2016). In addition, intercropping of crops having allelopathic potential suppresses the weeds and can give better weed control; thus, increasing the weed control in the main crop (Cheema et al. 2013; Jabran et al. 2015). Many studies have suggested that improving crop yields and productivity from existing agricultural lands rather than clearing more soils for food production is the most sustainable way to increase food security (Godfray et al. 2010; Garnett et al. 2013). In this scenario of "increase in crop yield and productivity from existing agricultural lands", intercropping is a sustainable farming practice that increases the crop yield per unit area per unit of time. On the other hand, in a single cropping system (no intercropping), the overall yield of the system is low due to weeds and pest pressure. In a single cropping system, weeds grow in the vicinity of crop plants and can cause shading and allelopathic effects, thereby decreasing the final yield of crops (Hauggaard-Nielsen et al. 2001; Jabran et al. 2017). This review highlights the cotton production in the world and Pakistan and cotton-based intercropping systems as a climate adoption strategy in the world.

Cotton production in the world

Worldwide cotton crop is grown on 35 million hectares (M ha) with a total production of 26.5 M tons of lint (OECD, 2022), which fulfills approximately 31% of the fibre needs of the world (Mollaee et al. 2019; Matloob et al. 2020). In addition, products like cottonseed oil and cotton meal are used in food, cosmetic industries pharmaceutical etc. (Munir et al. 2020), and thus it has significant economic importance in the economies of many countries. Therefore, growing cotton has been a fundamental component of agricultural countries for centuries, and >100 countries of the world grow cotton while > 150 countries are engaged in its trade either importing or export of cotton (Ahmad et al. 2018; Abbas and Ahmad, 2018). At the farm level, > 100 M farm families depend on cotton production. Although, cotton is produced in > 100 countries of the world 76% of the world's cotton is produced in only five countries, India (25%), China (23%), the USA (16%) Pakistan (7.67%) and Brazil (5.17%) (FAO, 2020; Matloob et al. 2020; OECD, 2021). However, the consumption of cotton is also higher in these countries particularly in China (35%), India (15) and Pakistan (10%) (Matloob et al. 2020) while the USA exports its cotton and its share in export of cotton is 41% (FAO, 2020). Pakistan holds a significant position as the world's fifth-largest cotton producer, contributing approximately 7.67% to the global cotton production-In Pakistan, 79% of cotton is grown in Punjab province followed by Sindh province (14%) while a small area of cotton exists in Baluchistan and Khyber Pakhtunkhwa provinces (GAIN, 2017; Rana et al. 2020). In Punjab province, it is mostly grown in districts Khanewal, Vehari, Multan, Muzafar Garh, Dera Ghazi Khan, Rajanpur, Rahim Yar Khan, Bahawalpur, Lodhran and Bahawal Nagar (Matloob et al. 2020). while, in Sindh, it is cultivated in Dadu, Ghotki, Benazirabad, Hyderabad, Nawabshah, Sukhar, Mirpur Khas, Nosheroferoz, Sanghar, Umar Kot, Khairpur, Jamshoro districts etc. (GAIN, 2017). Pakistan consumes approximately 10% of the world's cotton. Climatic conditions significantly affected the cotton production in Pakistan (Figure 2).

Due to climate change, several areas of Pakistan are facing severe heat and temperature stress during the growing season that is accompanied by water shortage. In addition, an increased attack of pest population pathogens has been recorded. The inconsistent pattern of rainfall during the sowing months of March, April, and May in all districts adversely impacts seed germination and the establishment of cotton plants. Severe rainfall at the flowering and boll formation stages encourages insect pest attack. Thus, the climate changes impose threats to cotton production and also to the well-being of farmers associated with cotton production and its linked industries. Integrated crop management strategies can help to mitigate the impacts of climatic changes to a certain extent. These strategies encompass various approaches such as breeding cotton for resistance, intercropping cotton with compatible crops (Table 1), implementing early sowing of cotton, and employing integrated nutrient management, disease control, and pest management tactics. By adopting these strategies, farmers can better manage the effects of climate change on cotton cultivation. Cotton production of Pakistan is shown in Figure 1.

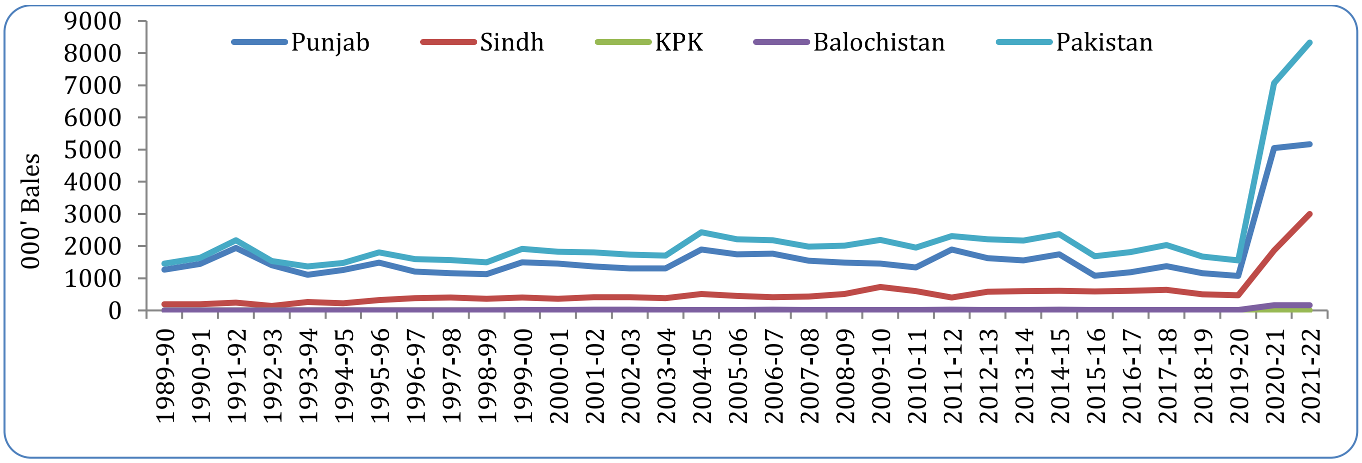

Figure 1. Cotton production by province in Pakistan (PCCC, 2023).

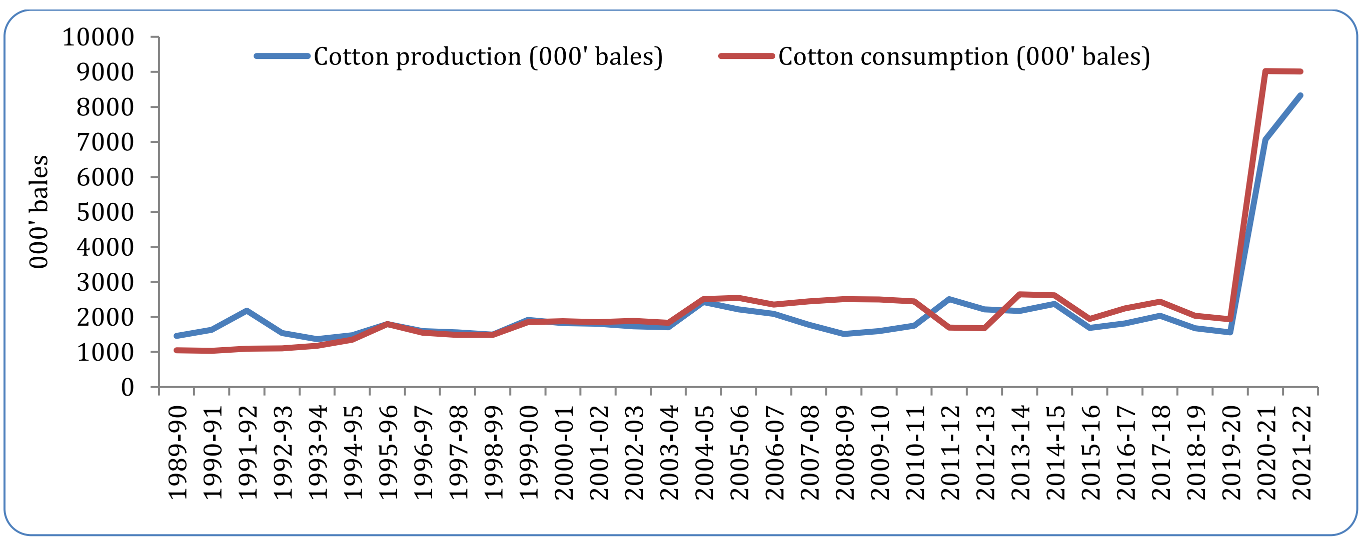

Figure 2. Cotton production and consumption in Pakistan (Pakistan Statistics, 2023).

Intercropping as a climate change adaptation strategy

The production and yield of field crops in developing countries is not as high as in developed countries of the world. Agricultural yield and production are controlled by the combination of climatic conditions, soil health, genetic resources, farm management decisions and technology. Although, the farmers try their best efforts to get higher yields but their efforts are in vain due to variable climatic events, water scarcity, soil fertility, and resistance of insect pests to many pesticides (Tariq et al. 2018; Matloob et al. 2020). Still, there is a huge yield gap between potential yield and achieved yield. On the other hand, the population of the world is growing rapidly and is expected to touch the 9.1 billion marks by 2050 (FAO, 2009; Ray et al. 2013; Mall et al. 2017). Therefore, it is time to get some new management practices such as intercropping to achieve high productivity while ensuring the sustainability of agriculture and environmental protection for the next generation.

Cotton-based intercropping systems

In developing countries, the majority of farmers have small landholdings, usually less than 5 ha (Tariq et al. 20172018; Usman et al. 2009). Our small farms are overloaded with surplus family labor, and yields on these farms are far low. Cotton is the most important cash crop of Pakistan; however, its yield is low (Amin et al. 2017, 2018ab; Khan et al. 2004; Rahman et al. 2018). Cotton has a position of foremost fiber besides cash crop, playing a crucial role to uphold the national economy. Intercropping is a companion planting technique of growing one crop alongside another on the same piece of land, aiming to increase yields from available growing space. The biodiversity of growing crops offers a variety of benefits besides predatory insects, which is not likely with monoculture. It may be mixed cropping, by planting a variety of well-suited plants collectively; alley or row cropping, in which different crops are planted with each other in rows; or temporal intercropping, which is a system of the fast-growing crop with a slow-growing crop. Cotton-based cropping systems have been reported as a promising strategy, particularly for small landholdings. Although a reduction in cotton yield by 8–31% is reported, however, more crop productivity from the single field with better net returns was recorded in intercropping than sole crop (Khan et al. 2012; Mohammad et al. 1991). An increase of 30–40% in farm income from different intercropping systems in cotton has been reported (Saeed et al. 1999). However, degree of such agroeconomic advantages mainly depends on the growth habit and nature of intercrop (Rao 1991). In traditional closely spaced single-row method of cotton planting, growing inter-crops does not remain convenient. It is particular that cotton must be planted in widely spaced multi-rows to ensure enough space for the facilitation of intercropping.

Intercropping is a sustainable farming practice that improves overall agricultural system efficiency by reducing the chances of crop failure due to well utilization of inputs or resources like water, nutrients and sunlight (Lulie, 2017; Hassen et al. 2017). Intercropping is a method of planting where one crop is planted alongside of another crop on the same piece of land to increase the yield of the planted area. While there may be some penalties in cotton yield total productivity and net return of the intercropping system is higher than individual crop (Matloob et al. 2020). Studies have shown a significant increase in farm income, ranging from 30% to 40%, as a result of various cotton-based intercropping practices (Pasha et al. 2020). It is important to note that the agro-economic benefits can vary depending on the specific type of intercrop utilized (Chaves et al. 2022). The benefits observed in cotton intercropping systems can be attributed to improved weed control and potential allelopathic effects on weed suppression (Jabran et al. 2020; He et al. 2021). However, it is crucial to consider the suitability of intercropping methods based on factors such as regional conditions, available resources, and most importantly, the acceptance of intercrops by the farming community (Khanal et al. 2021). Different regions have adopted various intercropping systems with variable planting geometries. Traditionally, conventional cotton production systems involved growing cotton in narrow rows, which made intercropping challenging (Ali et al. 2020). However, in recent methods, cotton is cultivated in wider beds or multiple rows with greater distances between them (Huang et al. 2018). This change in cultivation practices has facilitated the integration of intercropping in cotton farming and has many advantages (Figure 3).

Cotton-legume intercropping

Successful implementation of intercropping requires careful consideration before and during cultivation. It is important to recognize that intercropping can impact the vegetative growth of component crops, necessitating thoughtful management of spatial, temporal, and physical resources. The economic viability of intercropping largely hinges on selecting an appropriate planting pattern and compatible crop combinations (Seran and Brintha, 2009; Panda et al. 2020). Pulses and certain oilseed crops possess the advantageous characteristics of being more resilient to various abiotic stresses and having less competition with cotton, enabling them to complete their growth cycle more quickly. These attributes make legumes particularly suitable for intercropping systems. Legume crops such as soybean (*Glycine max* L.), groundnut (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* L.), mash bean (*Vigna mungo* L.) and mung bean (*Vigna radiata* L.) have been successfully intercropped with cotton due to their short growth duration and high drought tolerance (Jayakumar et al. 2008; Chi et al. 2019; Monicaa et al. 2020; Wang et al. 2022). Research reports indicate that the intercropping of legumes with cotton leads to improvements in overall yield and soil fertility (Kumar et al. 2018). The presence of legume intercrops enhances the soil's fertility status, particularly for nitrogen, thus providing a potential avenue for reducing the need for additional nitrogen fertilizers and promoting sustainable agricultural practices. By incorporating legumes as intercrops, farmers can not only enhance overall productivity but also benefit from the positive impact on soil fertility, ultimately contributing to more efficient nutrient management and reduced reliance on synthetic fertilizers.

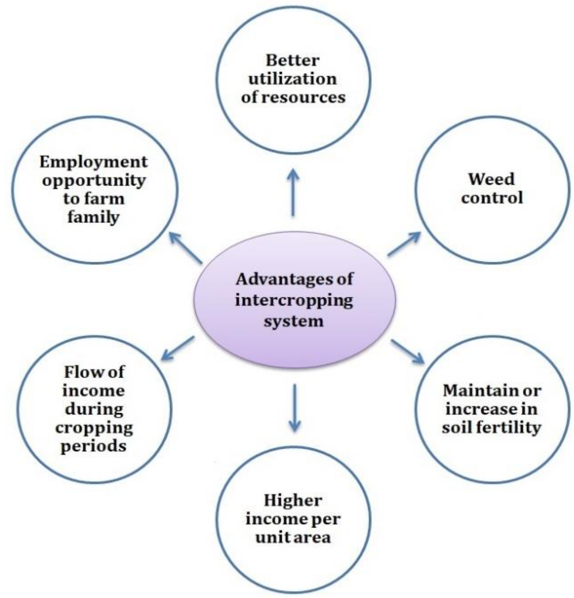

Figure 3. Advantages of intercropping systems.

Table 1. Intercropping of different crops with cotton.

Intercropping system	Country	References
Cotton + Mung bean	Pakistan	Khan et al. (2004)
Cotton + Peanut	China	Wang et al. (2022)
Cotton + Peanut	China	Chi et al. (2019)
Cotton + Sesame	China	Dang et al. (2011)
Cotton + Mung bean	Pakistan	Amin et al. (2018)
Cotton + Maize	China	Lu et al. (2017)
Cotton + Alfalfa	China	Lin et al. (2003)
Cotton + watermelon	Barnwell County	Millerand Greene (2018)
Cotton + groundnut	India	Maitra et al. 2001b
Cotton + cowpea	Zimbabwe	Rusinamhodzi et al. 2006
Cotton + sorghum	Pakistan	Aasim et al. 2008
Cotton + Cowpea	Malawi	Mwamlima et al. 2016
Cotton + Cluster bean	India	Kumar et al. 2017
Cotton + Cowpea	India	Kumar et al. 2017
Cotton + Mash bean	India	Vasavi and Sreerekha, 2017
Cotton + Cowpea	India	Rajpoot et al. 2018
Cotton + Okra	India	Rajpoot et al. 2018
Cotton + Groundnut	India	Maitra et al. 2001b
Cotton + Rice bean	Pakistan	Khan et al. 2004
Cotton + Mung bean	Bangladesh	Tabib et al. 2014
Cotton + onion	India	Jayakumar and Surendran, 2016

Cotton + Moth bean	India	Patel et al. 2017
Cotton + Soybean	India	Turkhede et al. 2017
Cotton + Onion	India	Marimuthua et al. (2014)
Cotton + Mung bean	India	Marimuthua et al. (2014)
Cotton + Beet root	India	Sankaranarayanan et al. (2012)
Cotton + Radish	India	Sankaranarayanan et al. (2012)
Cotton + Coriander	India	Sankaranarayanan et al. (2012)
Cotton + Dhaincha	India	Marimuthua et al. (2014)
Cotton + Cluster bean	India	Sankaranarayanan et al. (2012)
Cotton + Dolichos	India	Sankaranarayanan et al. (2012)
Cotton + Lucerne	India	Jayakumar and Surendran (2017
Cotton + Mash bean	India	Monicaa et al. (2020)
Cotton + Mung bean	India	Monicaa et al. (2020)
Cotton + Onion	India	Monicaa et al. (2020)
Cotton + peanut	China	Xie et al. (2022)
Cotton + Jujube	China	Wang et al. (2021)
Cotton + Mung bean	China	Liang et al. (2020)
Cotton + Garlic	China	Yue et al. (2019)
Cotton + Potato	China	Yue et al. (2019)

Legumes not only help in the utilization of atmospheric nitrogen but also help in residual nutrient buildup of the soil (Meena et al. 2018). Soybean being a leguminous crop adds organic nitrogen through its root nodules up to 250 kg per hectare besides releasing organic acids, enzymes and cytokines known for increasing the cotton yield (Kesavan, 2005; Chiduwa, 2021). Although legumes have the ability to fix the atmospheric nitrogen (biological nitrogen fixation) reports showed that the nitrogen fixation capacity of legumes increased when planted as intercrops rather than sole crop (Rusinamhodzi et al. 2006), and also reduced the nitrogen requirements of the accompanying crop. Reports showed that the nitrogen and phosphorus requirement of cotton was significantly less when grown with cowpea, mung bean, mash bean (Vigna mungo L.) and cluster bean (Cyamopsis tetragonoloba) as intercropping. There was a higher dry matter in cotton-legume intercropping which might be due to the higher availability of nitrogen and phosphorus (Jayakumar and Surendran 2017). Another benefit of legume crops is that they can be grown as bio-mulches to decrease soil evaporation losses and protect soil from erosion (Kocira et al. 2020). In short, intercropping of legumes with cotton is suitable for improving soil health and fertility (Gogoi et al. 2018; Huang et al. 2022) and higher monetary benefits (Jayakumar and Surendran 2017). Higher monetary return was obtained when cotton was intercropped with cluster beans, cowpeas, peanuts and mung beans (Sankaranarayanan et al. 2012; Rajpoot et al. 2018; Xie et al. 2022). However, the extent of monetary return differs according to the planting geometry of intercropping and crop species. Thus, cotton-legume intercropping is found to be a more productive system that only increases soil fertility but also the overall net return (Table 2).

Cotton-vegetable intercropping

Growing vegetables with cotton are an excellent practice as it not only fulfills the vegetable needs of the household but also earns a good profit. As cotton farmers continue to search for ways to enhance their profitability and better use of their resources, intercropping vegetables in cotton can be a great option. Intercropping of vegetables of different growth habits is very beneficial and economical (Rajpoot et al. 2018). In cotton-vegetable, there is a wide range where we can intercrop radish, turnip, beetroot, coriander, Indian squash (tinda), onion, cluster bean etc. (Sankaranarayanan et al. 2012; Marimuthua et al. 2014). This system of intercropping considerably increases the cotton yield and has no adverse effects on the quality of cotton. Rajpoot et al. (2018) intercropped okra (Abelmoschus esculentus L.) with cotton and observed higher cotton yield and net monetary returns than sole cotton.

Table 2. Yield of cotton and net returns from various intercropping systems in cotton.

Seed Cotton (t ha^{-1})	Net return ($)	Intercropping systems	References
5.19	1564	Peanut alone	Xie et al. (2022)
4.42	1212	Cotton alone	Xie et al. (2022)
7.16	1878	Cotton + peanut	Xie et al. (2022)
3.37	1055	Cotton alone at 90 cm row spacing	Rajpoot et al. (2018)
3.02	896	Cotton alone at 120 cm row spacing	Rajpoot et al. (2018)
3.83	1182	Cotton at 90 cm row spacing + Okra	Rajpoot et al. (2018)
3.37	973	Cotton at 120 cm row spacing + Okra	Rajpoot et al. (2018)
3.62	1088	Cotton at 90 cm row spacing + Cow pea	Rajpoot et al. (2018)
3.17	886	Cotton at 120 cm row spacing + Cow pea	Rajpoot et al. (2018)
3.57	979	Early March planted cotton (flat sowing)	Shah et al. (2016)
3.37	830	Late March planted cotton (flat sowing)	Shah et al. (2016)
3.21	3364	Wheat (bed sowing) + Early March planted cotton	Shah et al. (2016)
3.05	3129	Wheat (bed sowing) + Late March planted cotton	Shah et al. (2016)
3.33	3137	Wheat (ridge sowing) + Early March planted cotton	Shah et al. (2016)
3.09	3077	Wheat (ridge sowing) + Late March planted cotton	Shah et al. (2016)
1.78	506	Cotton alone	Marimuthua et al. (2014)
1.53	502	Cotton + onion	Marimuthua et al. (2014)
1.59	524	Cotton + mung bean	Marimuthua et al. (2014)
1.95	577	Cotton + dhaincha	Marimuthua et al. (2014)
2.62	442	Cotton alone	Sankaranarayanan et al. (2012)
2.78	505	Cotton + beet root + v. cowpea + cluster bean	Sankaranarayanan et al. (2012)
2.55	424	Cotton + radish + cluster bean + beet root	Sankaranarayanan et al. (2012)
2.74	492	Cotton + radish + cowpea + beet root	Sankaranarayanan et al. (2012)
2.68	472	Cotton + radish + dolichos + beet root	Sankaranarayanan et al. (2012)
2.91	546	Cotton + radish + beet root + coriander	Sankaranarayanan et al. (2012)
2.83	511	Cotton + cluster bean + v. cowpea + dolichos	Sankaranarayanan et al. (2012)
2.58	448	Cotton + cluster bean + cowpea + dolichos	Sankaranarayanan et al. (2012)
2.88	530	Cotton + beet root + v. cowpea + cluster bean	Sankaranarayanan et al. (2012)
-	307	Sole cotton	Sankaranarayanan et al. (2011)
-	1143	Cotton + radish + cluster bean + beet root	Sankaranarayanan et al. (2011)
-	1256	Cotton + radish + beet root + coriander	Sankaranarayanan et al. (2011)
1.97	485	Cotton alone	Iqbal et al. (2007)
1.15	600	Cotton double-row sorghum	Iqbal et al. (2007)
1.21	534	Cotton + single-row sorghum	Iqbal et al. (2007)
1.21	371	Cotton + double-row soybean	Iqbal et al. (2007)
1.36	397	Cotton + single-row soybean	Iqbal et al. (2007)
1.14	579	Cotton + double-row sesame	Iqbal et al. (2007)
1.19	486	Cotton + single-row sesame	Iqbal et al. (2007)

Similarly, cotton+ okra, and cotton+ beet root intercropping systems resulted in earlierand greater cotton of cotton and net returns (Sankaranarayanan et al. 2011; Rajpoot et al. 2018). Similarly, intercropping of cantaloupe in cotton gave a higher yield of cantaloupe (sweet melon) than sole cantaloupe. Although sweet melon decreased the cotton yield to some extent as compared to the sole cotton crop but overall net monetary return was maximum in cotton + cantaloupe rather those of monoculture cotton or cantaloupe (Eure et al. 2015). A study conducted by Marimuthua et al. (2014) examined the yield performance of different cotton-based intercropping systems. The research findings indicated that the cotton-onion intercropping system resulted in higher seed cotton yield compared to other systems evaluated. This suggests that integrating onion cultivation alongside cotton can lead to improved yields in cotton production. The study also highlighted that cotton-vegetable intercropping systems generally exhibited significant enhancements in yields and net returns. As a result, this intercropping approach can be particularly beneficial for small-scale farmers who rely heavily on crop cultivation for both food and economic benefits. By adopting cotton-vegetable intercropping, small farmers can potentially increase their overall productivity and economic returns, thereby contributing to their livelihoods.

Cotton-wheat relay cropping system

The delay in the sowing of wheat and the decrease in the cultivated area of wheat each year has caused major challenges to food security in developing countries like Pakistan (Hussain et al. 2013). Agriculturalists have introduced the technology of wheat cultivation in standing cotton (relay cropping), through which, by intercropping wheat in standing cotton, unusual delays in wheat cultivation can be avoided and complete pickings of the cotton crop can also be obtained. As cotton and wheat are cultivated in a large area of Pakistan and India, due to the long duration of the cotton crop, wheat cannot be sown at its best time and since the best time for wheat cultivation is November 15 (Shah et al. 2019). But during this period, cotton, especially Bt-varieties were present in the field with maximum fruits, so it was not possible for the farmer to fully harvest the cotton crop at that time. If the farmer waits for the harvesting of the cotton crop, there is an extraordinary delay in the sowing of the wheat crop, which will result in a huge yield reduction due to the short growing period of the wheat crop. Thus, the main goal of cotton-wheat relay cropping is to minimize the wheat and cotton yield losses, while wheat can be sown at the right time without any decline in wheat area. For the sowing of wheat in standing cotton, the farmers should irrigate their fields and when the fields reach to field capacity level, sow the seeds (60 kg/acre) that have been soaked in water for 8-10 hours. Furthermore, keep the fields wet for ten days after the sowing of wheat seeds so that the germination of wheat seeds after sowing can be increased (REEDS, 2022). Cotton-wheat relay intercropping system has the potential to increase the yield and profitability of both crops (Shah et al. 2016).

Intercropping of a relay crop of wheat in cotton showed that better light interception was recorded than the alone planted crop either wheat or cotton (Zhang et al. 2008). In Pakistan, Nasrullah et al. (2017) reported higher net profit when cotton was sown in standing wheat. Alike, Shah et al. (2016) conducted a 2-year research trial to monitor the profitability and production of relay cropping of wheat with cotton. They planted the cotton in beds and ridge-sown wheat. For comparison, sole cotton was also sown. Results showed that the benefit-cost ratio and net income were higher when cotton was intercropped in bed-sown wheat. Yield analyses of wheat relay cropping with cotton showed greater land equivalent ratio of 1.28 (Zhang et al. 2008).

The main aspects to be considered in the intercropping system

The success or failure of an intercropping system depends on several factors, such as the crops grown in intercropping or mixture can compete or strive spatially and temporally between species for resources (Panda et al. 2020). Successful intercropping requires careful consideration both before and during cultivation. The practice of intercropping has a significant impact on the vegetative growth of the crops involved, necessitating attention to spatial, temporal, and physical resources. To achieve economic viability, it is crucial to adapt the planting pattern and carefully select compatible crops (Seran and Brintha, 2009).

Selection of compatible crop

The selection of crop combinations plays a crucial role in the success of intercropping. Factors such as plant density, shading, and competition for nutrients can significantly reduce the yield of the main crop. To minimize plant competition and optimize yields, it is important to consider not only the spatial arrangement of the crops but also to choose those crops that are most adept at utilizing soil nutrients or plants such as crop that add some nutrients to the soil for example, intercropping of legumes (mung bean, mash bean, soybean, cluster bean, peanut etc.) with cotton suitable as compared to maize intercropping with cotton (Maitra et al. 2019). The inclusion of legumes in intercropping systems can lead to increased yields due to their efficient use of space and potential nitrogen contribution, which depends on factors such as crop densities, light interception, crop species, and nutrient availability (Nyawade et al., 2022). Therefore, the careful selection of compatible crops is vital in intercropping.

Time of planting

In intercropping systems, optimizing the relative planting time is a crucial factor, especially in many developing countries (Huang et al. 2018). The timing of planting plays a critical role in determining competition within species, directly impacting the yield of the component crops (Egbe, 2010). For example, when maize and soybean were intercropped together for 50 and 90 days, maize significantly decreased the biological yield of soybean during the early stage (Ahmed et al. 2018) however, when co-grew for 90 days, significantly decreased the pods plant^{-1}, number of seeds plant^{-1}, seed weight (g) and, overall soybean seed yield maize-soybean intercropping system (Ahmed et al. 2020). In relay intercropping systems that involve full-season cotton and wheat, the intergrowth period typically lasts between 40 to 50 days (Zhang et al. 2007). The duration of this intergrowth period is influenced by the sowing date of cotton. Early sowing dates allow for sufficient growth and development of cotton, but an extended intergrowth period can have varied effects on cotton's growth and development (Zhang et al. 2008). Previous studies have demonstrated that adjusting the sowing dates of intercropped cotton leads to differences in heat and radiation accumulation, not only during the intergrowth period but also throughout other growth stages of cotton. This, in turn, influences the growth patterns and yields of cotton (Khan et al. 2017; Hu et al. 2017). While early sowing of cotton can result in increased fruit branches, earlier flowers, and bolls, it does not necessarily guarantee higher cotton yields due to reduced boll-setting rates (Hu et al. 2017; Qi et al. 2018).

Alternatively, when cotton is planted late, it may fail to experience the optimal temperature conditions during its reproductive growth phase. As a consequence, there may be an inadequate accumulation of dry matter, an increase in immature bolls, and a decline in fibre quality (Khan et al. 2017; Hu et al. 2017). Therefore, optimizing the sowing date of both the component crop or intercrop and the main crop is crucial for enhancing yields in relay intercropping systems (Zhou et al. 2016). Careful consideration of the timing of sowing can help achieve a balance between maximizing cotton yield potential and ensuring favourable temperature conditions for optimal growth and development throughout the intercropping system.

Plant density

The density of plants in a given area is a critical factor that influences the success or failure of intercropping. It refers to the number of plants per unit area and has a significant impact on the growth and productivity of crops, whether they are grown individually or in combination with other crops. Selecting the appropriate plant density or spacing is essential to achieve optimal crop yield (Gebru, 2015). Competition can arise within a species (intraspecific) or between different species (interspecific). Based on a meta-analysis of various studies on multiple cropping, intraspecific competition tends to be more pronounced than interspecific competition. Occasionally, interspecific competition can lead to beneficial outcomes, while intraspecific competition tends to have adverse effects (Adler et al. 2018; Sandhu et al. 2020). Resource complementarity, which arises from niche differentiation, can explain the occurrence of beneficial effects in intercropping when two plant species are not competing for the same resources (Sandhu et al. 2020). In contrast, intraspecific competition intensifies with increasing population density, as plants sharing the same niche compete for resources such as water, nutrients, and light (Sandhu et al., 2020). Studies have indicated that low plant population density per unit area can result in reduced yields (Jeyakumaran and Seran, 2007). To achieve optimal plant density in intercropping systems, the seedling rate of each crop in the intercropping mixture is adjusted to be below its full rate. Planting at the full rates of each crop would lead to overcrowding and negatively impact yields. By reducing the seedling rates of each crop, intercropped crops have a better chance of yielding well within the mixture. This approach allows for a more balanced distribution of resources, including sunlight, water, and nutrients, among the intercropped plants. Optimizing plant density is a crucial aspect of establishing effective intercropping systems. Several studies emphasize the importance of considering plant density in intercropping practices (Sandhu et al. 2020; Jeyakumaran and Seran, 2007). By carefully adjusting the seedling rates of each crop in the intercropping mixture, farmers can promote healthier plant growth, minimize competition, and maximize overall yields within the intercropped system.

Table 3. Problems of different cotton-based intercropping systems and possible strategies (Matloob et al., 2020).

Issues	Strategy	References
Conflict of time between Bt cotton sowing and harvesting of wheat	Sowing time can be adjusted in Bt cotton by transplanting one-month-old cotton seedlings or nursery	Shah et al. (2017)
Low yield if wheat is sown late and/or low yield of cotton if cotton is sown late	Relay cropping with zero till increases the productivity of wheat. Intercropping with legumes and oilseeds crops increases the cotton yield and monetary returns from cropping system	Singh et al. (2016); Aladakattiet al. (2011); Buttar et al. (2017); Singh et al. (2016); Sajjad et al. (2018)
Nutrient management as greater requirements of nutrients for Bt cotton Weed infestation	Intercropping with groundnut, soybean and other leguminous crops. Incorporation of wheat and rice straw. Intercropping of cotton with green gram/sesbania using bio-inoculants such as Pseudomonas and *Azospirillium* that increases seed cotton yield and also suppresses the weed dry biomass	Singh et al. (2013); Singhand Ahlawat (2014). Sui et al. (2015); Yu et al. (2016) Sivakumar (2004); Vaiyapuri et al. (2010); Marimuthu and Subbian(2013
Aphid attack	Cotton intercropping with cowpea increases the population of natural enemy or predator of aphid	Fernandes et al. (2018)
Pink bollworm attack	Cotton-basil intercropping decreases pink bollworm infestation up to 50%	Schader et al. (2005)
Nematode management	Crop rotation (grain sorghum, maize, cotton-peanut and deep tillage can decrease the incidence of nematode and weed seeds.	Mueller et al. (2012)

Maturity of crop

In intercropping systems where two or more crops are cultivated together, it is beneficial if their peak growth periods do not overlap. This allows for one crop to reach maturity before its companion crop, reducing competition and promoting better growth and yield for both crops. A fast-growing crop intercrop may pull down the main crop growing with it and lower the final yield (Gardarin et al. 2022). The greatest complementary effects and yield advantages in intercropping are observed when the component crops have distinct growth periods, resulting in their major resource demands occurring at different times (Li et al. 2020). To optimize intercropping systems, it is advisable to select crops or varieties with varying maturity durations. By doing so, a rapidly maturing crop can complete its life cycle before the significant growth period of the other crop begins. This approach not only reduces competition between the crops but also facilitates staggered harvesting and the separation of different grain commodities.

To maximize the benefits of intercropping, it is important to consider the timing of peak nutrient demands among the component crops. Ideally, crops with different maturity periods should be selected, ensuring that their maximum nutrient and moisture requirements, as well as their need for aerial space and light, occur at separate times (Maitra et al. 2020). For example, in the intercropping of maize and mung bean, maize has a peak light demand around 60 days after planting, while mung bean is ready for harvest (Reddy and Reddi, 2007). This staggered growth pattern allows for efficient utilization of resources and minimizes competition between the crops. Therefore, selecting crops or varieties with different maturity dates is a very important factor in intercropping.

Intercrop productivity

The most important reason for growing two or more crops together is that it increases the productivity per unit of land. The land equivalent ratio (LER) has been developed by agricultural researchers and scientists to evaluate the performance of intercropping compared to yields obtained from pure stands. In research trials, separate plots are used to grow pure stands of individual crops and mixtures of crops. The yields from both the pure stands and the individual crops within the mixture are measured. This allows for an assessment of the land requirements per unit of yield. By comparing the yields of the main crop and the intercrops, it is possible to determine the yield advantage, if any, of intercropping over pure stands. Additionally, it is observed how much additional land would be needed in the pure stand to achieve the same yield as the intercrop (Iqbal et al., 2019). This calculated figure is known as the Land Equivalency Ratio (LER). To calculate the LER, the yields of the intercrops are divided by the yields of the pure stands for each component crop in the intercrop. The LER provides a measure of the productivity efficiency and resource utilization of intercropping systems (Zhang et al. 2021). Then, these two figures are added together. For example, cotton and soybean are intercropped together and yield from pure cotton, and pure soybean, and the yields from both cotton and soybean growing together in an intercrop are measured.

LER = (intercrop cotton / pure cotton) + (intercrop soybean / pure soybean)

When the Land Equivalency Ratio (LER) is equal to 1.0, it indicates that the land requirement for growing soybean and cotton together in an intercrop is the same as that for growing them in pure stands. In such cases, there is no advantage to intercropping over pure stands. LER values above 1.0 indicate an advantage to intercropping, while values below 1.0 indicate a disadvantage (Feng et al. 2021). For instance, an LER of 1.25 signifies that the total yield obtained from the intercrop would have required 25% more land if the crops were grown in pure stands. On the other hand, if the LER is 0.75, it means that the yield achieved in the intercrop is only 75% of what would have been obtained if the same amount of land had been used for pure stands. The LER provides a quantitative measure of the efficiency and productivity gained through intercropping, allowing researchers and farmers to assess the benefits of intercropping systems in terms of land utilization.

CONCLUSION

The climate is changing rapidly and the world's population is growing. In this context, we have to increase our productivity. The cotton-based intercropping system is imperative for farmers, particularly for small landholding farmers. There is maximum utilization of environmental resources to increase crop production in the intercropping system. Cereals, legumes, and vegetables can be intercropped with cotton. Each group gives numerous benefits in terms of yields and income over the sole cotton crop. Thus, an intercropping system is the need of time and is feasible and uses various resources more efficiently, resulting in higher productivity and monetary return.

REFERENCES

Aasim, M., Umer, E.M. and Karim, A. 2008. Yield and competition indices of intercropping cotton (*Gossypium hirsutum* L.) using different planting patterns. Ankara üniversitesi ziraat fakültesi, 14: 326–333.

Abbas, Q. and Ahmad, S. 2018. Effect of different sowing times and cultivars on cotton fiber quality under stable cotton-wheat cropping system in southern Punjab, Pakistan. Pakistan Journal of Life and Social Sciences, 16: 77–84.

Abbas, S. 2020. Climate change and cotton production: an empirical investigation of Pakistan. Environmental Science and Pollution Research, 27: 29580-29588.

Adler, P.B., Smull., Beard, D. K.H., Choi, R.T., Furniss, T., Kulmatiski, A., Meiners, J.M., Tredennick, A.T., & Veblen, K.E. 2018. Competition and coexistence in plant communities: Intraspecific competition is stronger than interspecific competition. Ecological Letters, 21: 1319–1329

Ahmad, S., Iqbal, M., Muhammad, T., Mehmood, A., Ahmad, S. and Hasanuzzaman, M. 2018. Cotton productivity enhanced through transplanting and early sowing. Acta Scientiarum. Biological Sciences, 40: 34610.

Ahmed, S., Raza, M. A., Yuan, X., Du, Y., Iqbal, N., Chachar, Q. and Yang, W. 2020. Optimized planting time and co-growth duration reduce the yield difference between intercropped and sole soybean by enhancing soybean resilience toward size-asymmetric competition. Food and Energy Security, 9: e226.

Ahmed, S., Raza, M., Zhou, T., Hussain, S., Khalid, M., Feng, L. and Yang, W. 2018. Responses of soybean dry matter production, phosphorus accumulation, and seed yield to sowing time under relay intercropping with maize. Agronomy, 8: 282–299.

Aladakatti, Y.R., Hallikeri, S.S., Nandagavi, R.A., Hugar, A.Y. and Naveen, N.E. 2011. Effect of intercropping of oilseed crops on growth, yield and economics of cotton (Gossypium hirsutum) under rainfed conditions. Karnataka Journal of Agricultural Sciences, 24.

Ali, H., Sarwar, N., Ahmad, S., Farooq, O., Nahar, K. and Hasanuzzaman, M. 2020. Cotton-based intercropping systems. In Cotton production and uses (pp. 321-340). Springer, Singapore.

Amin, M. R., Islam, M. S., Hasan, M. K. and Sabagh, A. E. 2018. Improvement of production and net economic return through intercropping of upland cotton with mungbean. Azarian Journal of Agriculture, 5: 67-75.

Azhar, M.T. and Rehman, A. 2018. Overview on effects of water stress on cotton plants and productivity. In: "Biochemical, Physiological and Molecular Avenues for Combating Abiotic Stress Tolerance in Plants", pp. 297-316. Academic Press.

Bhatti, M. M. A. and Naqvi, S. A. H. 2020. Cotton Diseases and Disorders Under Changing Climate. In Cotton Production and Uses (pp. 271-282). Springer, Singapore.

Bibi, A., Oosterhuis, D. and Gonias, E. 2008. Photosynthesis, quantum yield of photosystem II and membrane leakage as affected by high temperatures in cotton genotypes. Journal of Cotton Science, 12: 150-159.

Buttar, G.S., Thind, H.S., Sekhon, K.S., Kaur, A., Gill, R.S., Sidhu, B.S. and Aujla, M.S. 2017. Management of saline-sodic water in cotton-wheat cropping system. Journal of Agriculture Science and Technology, 19: 465–474

Carmo-Silva, A.E. 2012. Decreased CO_2 availability and inactivation of Rubisco limit photosynthesis in cotton plants under heat and drought stress in the field. Environmental and Experimental Botany, 83: 1-11.

Chao, H., Zhang, D. H., Xu, L. and Liao, K. 2007. Study on microclimatic horizontal distribution law of apricot–cotton intercropping system. Journal of Xinjiang Agricultural University, 30: 35-39.

Chaves, A. P., Bezerra Neto, F., Lima, J. S. S., Silva, J. N., Santos, E. C., Nunes, R. L. C. and Lino, V. A. D. S. 2022. Bio-agroeconomic returns in beet-cowpea intercropping by optimization of population densities and spatial arrangements. Acta Scientiarum. Agronomy, 44.

Cheema, Z.A., Farooq, M. and Khaliq, A. 2013. Application of allelopathy in crop production: a success story from Pakistan. Allelopathy: current trends and future applications, 113-143.

Chi, B., Zhang, Y., Zhang, D., Zhang, X., Dai, J. and Dong, H. 2019. Wide strip intercropping of cotton and peanut combined with strip rotation increases crop productivity and economic returns. Field Crops Research, 243, 107617.

Chiduwa, M. S. 2021. Improving the legume-rhizobium symbiosis in Zimbabwean Agriculture: A study of rhizobia diversity & symbiotic potential focussed on soybean root nodule bacteria (Doctoral dissertation, Murdoch University).

Dabbert, T. and Gore, M.A. 2014. Challenges and perspectives on improving heat and drought stress resilience in cotton. Journal of Cotton Science, 18: 393-409.

Dang, X., Liu, J., Paniguli, A., Wang, J., Wei, C., Zhang, L. and Li, L. 2011. Cotton fiber quality in cotton-based intercropping systems. China Cotton, 38: 18–20. (in Chinese)

Dong, H. 2006. Yield, quality and leaf senescence of cotton grown at varying planting dates and plant densities in the Yellow River Valley of China. Field Crops Research, 98: 106-115.

Egbe, O.M. 2010. Effects of plant density of intercropped soybean with tall sorghum on the competitive ability of soybean and economic yield at Otobi, Benue State, Nigeria. Journal of Cereals and Oilseeds, 1: 1-10.

Ekinci, R. 2017. The Effects of High Temperature Stress on some Agronomic Characters in Cotton. Pakistan Journal of Botany, 49: 503-508.

Eure, P.M., Culpepper, A.S., Merchant, R.M., Roberts, P.M. and Collins, G.C. 2015. Weed control, crop response, and profitability when intercropping cantaloupe and cotton. Weed Technology, 29: 217-225.

FAO. 2009. Global agriculture towards 2050. Paper presented at the how to feed the world 2050: high-level expert forum, Rome, 12–13.

FAO. 2020. Statistical database, Food and Agriculture Organization, United Nation

Feng, C., Sun, Z., Zhang, L., Feng, L., Zheng, J., Bai, W., Gu, C., Wang, Q., Xu, Z. and van der Werf, W. 2021. Maize/peanut intercropping increases land productivity: A meta-analysis. Field Crops Research, 270: 108-208.

Fernandes, F.S., Godoy, W.A.C., Ramalho, F.S., Garcia, A.G., Santos, B.D.B., Malaquias, J.B. 2018. Population dynamics of Aphis gossypii Glover and Aphis craccivora Koch (Hemiptera: Heteroptera: Aphididae) in sole and intercropping systems of cotton and cowpea. The Annals of the Brazilian Academy of Sciences, 90: 311–323

GAIN (Global Agricultural Information Network). 1 April 2017. Archived from the original (PDF) on 30 January 2017. Retrieved 13 November 2015.

Gardarin, A., Celette, F., Naudin, C., Piva, G., Valantin-Morison, M., Vrignon-Brenas, S., ... & Médiène, S. (2022). Intercropping with service crops provides multiple services in temperate arable systems: a review. Agronomy for Sustainable Development, 42(3), 1-23.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D. 2013. Sustainable intensification in agriculture: Premises and policies. Science, 341, 33–34.

Gebru, H. 2015. A review on the comparative advantages of intercropping to mono-cropping system. Journal of Biology, Agriculture and Healthcare, 5: 1-13.

Glaze-Corcoran, S., Hashemi, M., Sadeghpour, A., Jahanzad, E., Afshar, R. K., Liu, X. and Herbert, S. J. 2020. Understanding intercropping to improve agricultural resiliency and environmental sustainability. Advances in Agronomy, 162: 199-256.

Godfray, H.C.J., J.R. Beddington, I.R., Crute, I., Hadded, D., and Lawrence. 2010. Food Security the challenge of feeding 9 million people, Science,327, 812- 818.

Gogoi, N., Baruah, K. K. and Meena, R. S. 2018. Grain legumes: impact on soil health and agroecosystem. In Legumes for soil health and sustainable management. Springer, Singapore, 511-539.

Gregory, P., Ingram, J.S. and Brklacich, M. 2005. Climate change and food security, Philosophical Transactions of the Royal Society B. Biological Sciences, 360: 2139 - 2148

Grigorova, B. 2011. Combined drought and heat stress in wheat: Changes in some heat shock proteins. Biologia Plantarum, 55: 105-111.

Hassen, A., Talore, D. G., Tesfamariam, E. H., Friend, M. A., and Mpanza, T. D. E. 2017. Potential use of forage-legume intercropping technologies to adapt to climate change impacts on mixed crop-livestock systems in Africa: a review. Regional Environmental Change, 17: 1713-1724.

Hauggaard-Nielsen, H., Ambus, P. and Jensen, E.S. 2001. Interspecific competition, N use and interference with weeds in pea–barley intercropping. Field crops research, 70:101-109.

He, X., Xie, H., Gao, D., Khashi U. Rahman, M., Zhou, X., & Wu, F. 2021. Biochar and intercropping with potato–onion enhanced the growth and yield advantages of tomato by regulating the soil properties, nutrient uptake, and soil microbial community. Frontiers in microbiology, 12: 695447.

Howden, S.M., Soussana, J.F., Tubiello, F.N., Chhetri, N., Dunlop, M. and Meinke, H. 2007. Adapting agriculture to climate change. Proceedings of the National Academy of Sciences of the United States of America, 104: 19691–19696.

Hu, W., Chen, M.L., Zhao, W.Q., Chen, B.L., Wang, Y.H., Wang, S.S., Meng, Y., L. Zhou, Z.G. 2017. The effects of sowing date on cottonseed properties at different fruiting-branch positions. Journal of Integrative Agriculture, 16: 1322–1330.

Huang, B., Yuan, Z., Zheng, M., Liao, Y., Nguyen, K.L., Nguyen, T.H., Sombatpanit, S. and Li, D. 2022. Soil and water conservation techniques in tropical and subtropical Asia: A Review. Sustainability, 14: 5035.

Huang, C., Shen, C., Wen, T., Gao, B., Zhu, D., Li, X. and Lin,

Z. 2018. SSR-based association mapping of fiber quality in upland cotton using an eight-way MAGIC population. Molecular Genetics and Genomics, 293: 793-805.

Huang, Z., Cui, C., Cao, Y., Dai, J., Cheng, X., Hua, S., & Zhong, Z. 2022. Tea plant–legume intercropping simultaneously improves soil fertility and tea quality by changing Bacillus species composition. Horticulture Research, 9.

Iqbal, J., Cheema, Z.A. and An, M. 2007. Intercropping of field crops in cotton for the management of purple nutsedge (Cyperus rotundus L.). Plant and Soil, 300: 163-171.

Iqbal, M.A., Hamid, A., Hussain, I., Siddiqui, M.H., Ahmad, T., Khaliq, A. and Ahmad, Z. 2019. Competitive indices in cereal and legume mixtures in a South Asian environment. Agronomy Journal, 111: 242-249.

Iqbal, N., Hussain, S., Ahmed, Z., Yang, F., Wang, X., Liu, W. and Liu, J. 2019. Comparative analysis of maize–soybean strip intercropping systems: a review. Plant Production Science, 22: 131-142.

Jabran, K. 2017. Allelopathy: Introduction and Concepts. – Springer: Cham, Switzerland, 1–12.

Jabran, K., Mahajan, G., Sardana, V. and Chauhan, B.S. 2015. Allelopathy for weed control in agricultural systems. Crop protection, 72: 57-65.

Jabran, K., Nawaz, A., Uludag, A., Ahmad, S. and Hussain, M. 2020. Cotton relay intercropping under continuous cotton-wheat cropping system. In Cotton Production and Uses (pp. 311-320). Springer, Singapore.

Jans, Y., von Bloh, W., Schaphoff, S. and Müller, C. 2021. Global cotton production under climate change–Implications for yield and water consumption. Hydrology and Earth System Sciences, 25: 2027-2044.

Jayakumar, M. and Surendran, U. 2016. Intercropping and balanced nutrient management for sustainable cotton production. Journal of Plant Nutrition, 40: 632–644.

Jayakumar, M. and Surendran, U. 2017. Intercropping and balanced nutrient management for sustainable cotton production. Journal of Plant Nutrition, 40: 632-644.

Jayakumar, M., Ponnuswamy, K. and Amanullah, M.M. 2008. Influence of Sources of Nitrogen and Intercropping on Pest Incidence, Yield Attributes and Yield of Cotton. Journal of Applied Science and Research, 4: 224228.

Jeyakumaran, J. and Seran, T.H. 2007. Studies on intercropping capsicum (Capsicum annum L.) with bushitao (Vigna unguiculata L.) Proceedings of the 6th Annual Research Session, Oct. 18-19, Trinconalee campus, EUSL,431-440.

Keshavan, N.D., Chowdhary, P.K., Haines, D.C. and González, J.E. 2005. L-Canavanine made by Medicago sativa interferes with quorum sensing in Sinorhizobium meliloti. Journal of Bacteriology, 187: 8427-8436.

Khan, A., Najeeb, U., Wang, L., Tan, D. K. Y., Yang, G., Munsif, F. and Hafeez, A. 2017. Planting density and sowing date strongly influence growth and lint yield of cotton crops. Field Crops Research, 209: 129-135.

Khan, A., Najeeb, U., Wang, L., Tan, D.K.Y., Yang, G., Munsif, F., Ali, S. and Hafeez, A. 2017. Planting density and sowing date strongly influence growth and lint yield of cotton crops. Field Crops Research, 209: 129-135.

Khan, M. B. and Khaliq, A. 2004. Studies on intercropping summer fodders in cotton. Journal of Scientific Research,15(3): 325-331.

Khanal, U., Stott, K. J., Armstrong, R., Nuttall, J. G., Henry, F., Christy, B. P. and O'Leary, G. J. 2021. Intercropping—evaluating the advantages to broadacre systems. Agriculture, 11(5): 453.

Kimball, B. A. 2016. Crop responses to elevated CO2 and interactions with H2O, N, and temperature, Current Opinion in Plant Biology, 31: 36–43.

Kocira, A., Staniak, M., Tomaszewska, M., Kornas, R., Cymerman, J., Panasiewicz, K. and Lipińska, H. 2020. Legume cover crops as one of the elements of strategic weed management and soil quality improvement. A review. Agriculture, 10(9): 394.

Kumar, N., Hazra, K. K., Nath, C. P., Praharaj, C. S. and Singh, U. 2018. Grain legumes for resource conservation and agricultural sustainability in South Asia. Legumes for soil health and sustainable management, 77-107.

Kumar, R., Turkhede, A. B., Nagar, R. K. and Nath, A. 2017. Effect of different intercrops on growth and yield attributes of American cotton under dryland conditions. International Journal of Current Microbiology and Applied Sciences, 6(4): 754-761.

Li, C., Hoffland, E., Kuyper, T. W., Yu, Y., Li, H., Zhang, C. and van der Werf, W. 2020. Yield gain, complementarity and competitive dominance in intercropping in China: A meta-analysis of drivers of yield gain using additive partitioning. European Journal of Agronomy, 113: 125987.

Li, H., Li, Q., Wang, D., Liu, J., Zhang, J. and Lu, Y. 2020. Effect of a cotton intercrop on spider mite populations in jujube trees. Journal of Asia-Pacific Entomology, 23(1): 167-171.

Liang, J., He, Z. and Shi, W. 2020. Cotton/mung bean intercropping improves crop productivity, water use efficiency, nitrogen uptake, and economic benefits in the arid area of Northwest China. Agricultural Water Management, 240: 106277.

Lin, R., Liang, H., Zhang, R., Tian, C. and Ma, Y. 2003. Impact of alfalfa/ cotton intercropping and management on some aphid predators in China. Journal of Applied Entomology, 126: 33–36.

Loka, D. and Oosterhuis, D. 2010. Effect of high night temperatures on cotton respiration, ATP levels and carbohydrate content. Environmental and Experimental Botany, 68: 258-263

Lu, X. Y., Li, S. Y., Zhu, J. B., Cheng, F. R., Liu, F. Z., Jiang, B. L. and Yu, C. 2017. Effect of spring corn and cotton intercropping on the population dynamics of Aphis gossypii and Rhopalosiphum maidis. China Cotton, 44: 24-27.

Lulie, B. 2017. Intercropping practice as an alternative pathway for sustainable agriculture: A review. Academic Research Journal of Agricultural Science and Research, 5(6): 440.

Maitra, S., Palai, J. B., Manasa, P. and Kumar, D. P. 2019. Potential of intercropping system in sustaining crop productivity. International Journal of Agriculture, Environment and Biotechnology, 12(1): 39-45.

Maitra, S., Samui, R.C., Roy, D.K. and Mondal, A.K. 2001b. Effect of cotton based intercropping system under rainfed conditions in Sundarban region of West Bengal. Indian Agriculturist, 45(3-4): 157–162

Maitra, S., Shankar, T. and Banerjee, P. 2020. Potential and advantages of maize-legume intercropping system. Maize-Production and Use, 1-14.

Mall, R.K., Gupta, A. and Sonkar, G. 2017. Effect of climate change on agricultural crops. In Current developments in biotechnology and bioengineering (pp. 23-46). Elsevier.

Manpreet-Singh, M.S., Mahal, J.S., Sidhu, H.S., Manes, G.S., Jat, M.L. and Yadvinder-Singh, Y.S. 2016. Development and feasibility of innovative relay seeders for seeding wheat into standing cotton using a high clearance tractor in a cotton-wheat system.

Marimuthu, S. and Subbian, P. 2013. Integrated nutrient management on weed dynamics of cotton-based cropping systems in South India. SAARC Journal of Agriculture, 11: 7–22

Marimuthua, S., Surendran, U. and Subbian, P. 2014. Productivity, nutrient uptake and post-harvest soil fertility as influenced by cotton-based cropping system with integrated nutrient management practices in semi-arid tropics. Archives of Agronomy and Soil Sciences, 60: 87–101

Matloob, A., Aslam, F., Rehman, H.U., Khaliq, A., Ahmad, S., Yasmeen, A. and Hussain, N. 2020. Cotton-based cropping systems and their impacts on production. Cotton Production and Uses: Agronomy, Crop Protection, and Postharvest Technologies, pp.283-310.

Meena, B. L., Fagodiya, R. K., Prajapat, K., Dotaniya, M. L., Kaledhonkar, M. J., Sharma, P. C. and Kumar, S. 2018. Legume green manuring: an option for soil sustainability. In Legumes for soil health and sustainable management (pp. 387-408). Springer, Singapore.

Miller, G., & Greene, J. (2018). Intercropping seedless watermelon and cotton. Horticulture Science, 53: 1799–1803.

Mohler, C.L. and Johbson, S.E. 2009. In: Crop rotation on organic farms. A planning manual. Natural Resource Agriculture and Engineering Service, Ithaca, New York, USA. p. 163

Mollaee, M., Mobli, A., Mutti, N. K., Manalil, S., & Chauhan, B. S. 2019. Challenges and opportunities in cotton production. Cotton production, 371-390.

Monicaa, M., Vaiyapuri, K., Kamalakannan, A. and Sakthivel, N. 2020. Growth and yield of ELS cotton as influenced by method of planting, intercrops and fertilizer management in summer season. Journal of Pharmacognosy and Phytochemistry, 9(4): 1973-1977.

Mueller, J., Koenning, S., Kirkpatrick, T., Kemerait, B., Overstreet, C. and Nichols, R. 2012. Managing nematodes in cotton-based cropping systems. Cotton Incorporated, 1-4.

Munir, H., Rasul, F., Ahmad, A., Sajid, M., Ayub, S., Arif, M., and Khan, M. A. 2020. Diverse uses of cotton: From products to byproducts. In Cotton production and uses (pp. 629-641). Springer, Singapore.

Mwamlima, L. H., Kabambe, V. H., Mhango, W. G., & Nyirenda, G. K. C. (2016). Effects of intercropping on growth and yield of intercropped cotton (Gossypium hirsutum) and cowpea (Vigna unguiculata L. Walp) in Malawi. Agricultural Science Research Journal, 6(12): 303-312.

Nasrullah, H.M., Aslam, M., Akhtar, M., Ali, B., Majid, A., Akram, M. and Farooq, U. 2017. Relay cropping of cotton in standing wheat: an innovative approach for enhancing the productivity and income of small farm. Romamian Agriculture Research, 34: 87-195.

Nyawade, S. O., Karanja, N. N., Gachene, C. K., Gitari, H. I., Schulte-Geldermann, E. and Parker, M. 2020. Optimizing soil nitrogen balance in a potato cropping system through legume intercropping. Nutrient Cycling in Agroecosystems, 117(1): 43-59.

OECD/FAO, 2022. ''OECD-FAO Agricultural Outlook OECD Agriculture statistics (database)'', http://dx.doi.org/10.1787/agr-outl-data

OECD/FAO, 2021. "OECD-FAO Agricultural Outlook Reports." Data Retrieved from OECD iLibrary, Https://Stats.oecd.org/BrandedView.aspx.

Pakistan statistics, 2023. Cotton and consumption estimate of Pakistan during current season.

Panda, S.K., Panda, P., Pramanick, B., Shankar, T., Praharaj, S., Saren, B.K., Gitari, H.I., Brahmachari, K., Hossain, A. and Maitra, S. 2020. Advantages of cotton based intercropping system: A review. International Journal of Bioresource Science, 7(2): 51-57.

Pasha, M. L., Sridevi, S., Ramana, M. V., Reddy, P. R. R., Goverdhan, M. and Rao, P. J. M. 2020. Yield, Economics and Cropping Indices of Cotton+ Pigeon Pea Inter Cropping under Varying Row Ratios in Rained Conditions. International Journal of Current Microbiology and Applied Sciences, 9(2): 1464-1472.

Patel, D.G., Patel, C.K., Singh, R.N. and Patel, N.I. 2017. Intercropping study in Bt. cotton under rainfed condition of Kutch region of Gujarat (Gossypium hirsutum L.). International Journal of Science, Environment and Technology, 6(6): 3484 – 3488.

PCCC, 2023. Pakistan Central Cotton Committee) Bulletins.

Pettigrew, W. T. 2016. Cultivar variation in cotton photosynthetic performance under different temperature regimes. Photosynthetica, 54: 502-507.

Qi, J., Dai, J., Sun, X. and Dong, H. 2018. Short-Season Cotton: Mechanism of Early Maturity and its Cultivation. Cotton Science, 30: 406-413.

Rajpoot, S. K., Rana, D. S. and Choudhary, A. K. 2018. Bt-cotton–vegetable-based intercropping systems as influenced by crop establishment method and planting geometry of Bt-cotton in Indo-Gangetic plains region. Current Science, 115(3): 516-522.

Rana, A. W., Ejaz, A. and Shikoh, S. H. 2020. Cotton crop: A situational analysis of Pakistan. Intl Food Policy Res Inst.

Ray, D. K., Mueller, N. D., West, P. C. and Foley, J. A. 2013. Yield trends are insufficient to double global crop production by 2050. PloS one, 8(6).

Reddy, T.Y., Reddi, G.H.S. 2007. Principles of Agronomy. Kalyam Publishers, India, pp. 468-489.

Rural Education and Economic Development Society (REEDS), Pakistan. Manual for sowing of wheat crop. pp5.

Rusinamhodzi, L., Murwira, H.K., Nyamangara, J. 2006. Cotton–cowpea intercropping and its N2 fixation capacity improves yield of a subsequent maize crop under Zimbabwean rain-fed conditions. Plant and Soil, 287: 327–336.

Sajjad, A., Anjum, S. A., Ahmad, R. and Waraich, E. A. 2018. Relay cropping of wheat (*Triticum aestivum* L.) in cotton (*Gossypium hirsutum* L.) improves the profitability of the cotton-wheat cropping system in Punjab, Pakistan. Environmental Science and Pollution Research, 25: 782-789.

Sandhu, R. K., Boyd, N. S., Sharpe, S., Guan, Z., Qiu, Q., Luo, T. and Agehara, S. 2020. Management of relaycropped strawberry and eggplant to maximize yield and economic return. HortScience, 55(7): 1083-1089.

Sankaranarayanan, K., Nalayini, P. and Praharaj, C.S. 2012. Multi-tier cropping system to enhance resource utilization, profitability and sustainability of Bt cotton (Gossypium hirsutum) production system. Indian Journal Agricultural Science, 82(12): 1044–50.

Sankaranarayanan, K., Nalayini, P., Sabesh, M., Rajendran, K., Nachane, R. P. and Gopalakrishnan, N. 2011. Multi-tier cropping system for profitability and stability in Bt cotton production. Indian Journal of Agricultural Sciences, 82(12):1044-1050

Sawan, Z. M. (2018). Climatic variables: Evaporation, sunshine, relative humidity, soil and air temperature and its adverse effects on cotton production. Information processing in agriculture, 5(1): 134-148.

Schader, C., Zaller, J.G. and Köpke, U. 2005. Cotton-Basil intercropping: Effects on pests, yields and economical parameters in an organic field in Fayoum, Egypt. Biological Agriculture and Horticulture, 23:59–72

Seran, T.H. and Brintha, I. 2009. Study on determining a suitable pattern of capsicum (Capsicum annum L.)-vegetable cowpea (Vigna unguiculata L.) intercropping. Karnataka Journal of Agricultural Sciences, 22(5):1153-1154.

Shah, M.A., Farooq, M. and Hussain, M. 2016. Productivity and profitability of cotton–wheat system as influenced by relay intercropping of insect resistant transgenic cotton in bed planted wheat. European Journal of Agronomy, 75: 33.

Shah, M.A., Farooq, M. and Hussain, M. 2017. Evaluation of transplanting Bt cotton in a cotton–wheat cropping system. Experimental Agriculture, 53:227–241

Shah, T., Latif, S., Khan, H., Munsif, F. and Nie, L. 2019. Ascorbic acid priming enhances seed germination and seedling growth of winter wheat under low temperature due to late sowing in Pakistan. Agronomy, 9(11):757.

Singh, M., Sidhu, H.S., Mahal, J.S., Manes, G.S., Jat, M.L., Mahal, A.K., Singh, P., Singh, Y. 2016. Relay sowing of wheat in the cotton–wheat cropping system in North-West India: technical and economic aspects. Experimental Agriculture, 53:539–552

Singh, R.J., Ahlawat, I.P.S. and Singh, S. 2013. Effects of transgenic Bt cotton on soil fertility and biology under field conditions in subtropical Inceptisol. Environmental Monitoring and Assessment, 185:485–495

Sivakumar, S.D. 2004. Performance of vegetable intercropping systems and sources of nutrients supply on sustainable yield of rainfed cotton. Ph.D. Dissertation, Agricultural College and Research Institute, Madurai. Tamil Nadu Agric. Univ., Coimbatore, India

Sui, N., Zhou, Z., Yu, C., Liu, R., Yang, C., Zhang, F., Song, G., and Meng, Y. 2015. Yield and potassium use efficiency of cotton with wheat straw incorporation and potassium fertilization on soils with various conditions in the wheat-cotton rotation system. Field Crops Research, 172:132–144

Tabib, F.A.I., Karim, M.A., Haque, M.M., Khaliq, Q.A. and Solaiman, A.R.M. 2014. Effect of planting arrangements on productivity of cotton + mungbean intercropping systems. Bangladesh Agronomy Journal, 17(1): 11–22.

Tariq, M., Afzal, M.N., Muhammad, D., Ahmad, S., Shahzad, A.N., Kiran, A. and Wakeel, A. 2018. Relationship of tissue potassium content with yield and fiber quality components of Bt cotton as influenced by potassium application methods. Field Crops Research, 229:37–43

Turkhede, A.B., Nagdeve, M.B., Karunakar, A.P., Gabhane, V.V., Mohod, V.D. and Mali, R.S. 2017. Diversification in cotton-based cropping system under mechanization in rainfed condition of Vidarbha of Maharashtra, India. International Journal of Current Microbiology and Applied Sciences, 6(9): 2189–2206.

USDA, GAIN Report Assessments of commodity and trade issues made by USDA staff and not necessarily statements of official U.S. Government policy, April, 2017.

Vaiyapuri, K., Amanullah, M.M., Rajendran, K. and Sathyamoorthi, K. 2010. Intercropping unconventional green manures in cotton: An organic approach for multiple benefits–A review. Asian Journal of Plant Sciences, 9:223–226

Vasavi, M. and Sreerekha, M. 2017. Effect of legume intercropping on competition indices and returns of Bt cotton. Journal of Cotton Research Development, 31(2): 279–282.

Wang, G., Wang, D., Zhou, X., Shah, S., Wang, L., Ahmed, M. and Fahad, S. 2022. Effects of Cotton–Peanut Intercropping Patterns on Cotton Yield Formation and Economic Benefits. Frontiers in Sustainable Food Systems, 6: 900230.

Wang, X. Y., Yang, T., Shen, L., Zhang, W. L., Wan, S. M., Zhang, W. and Li, L. H. 2021. Formation of factors influencing cotton yield in jujube–cotton intercropping systems in Xinjiang, China. Agroforestry Systems, 95(1): 177-189.

Xie, W., Zhang, K., Wang, X., Zou, X., Zhang, X., Yu, X. and Si, T. 2022. Peanut and cotton intercropping increases productivity and economic returns through regulating plant nutrient accumulation and soil microbial communities. BMC Plant Biology, 22(1): 1-14.

Yakubu, H., Kwari, J.D. and Sandabe, M.K. 2010. Effect of phosphorus fertilizer on nitrogen fixation by some grain legume varieties in Sudano–Sahelian Zone of North Eastern Nigeria. Nigerian journal of Basic and Applied sciences, 18(1): 44-49.

Yu, C., Wang, X., Hu, B., Yang, C., Sui, N., Liu, R., Meng, Y. and Zhou, Z. 2016. Effects of wheat straw incorporation in cotton-wheat double cropping system on nutrient status and growth in cotton. Field Crops Research, 197:39–51

Yue, H. and Sun, C. 2019. November. Analysis on the Key Problems of Chinese Cotton Full Mechanization Based on System Engineering Theory. In IOP Conference Series: Materials Science and Engineering (Vol. 688, No. 5, p. 055077). IOP Publishing.

Zaefarian, F. and Rezvani, M. 2016. Environmental Stresses in Soybean Production Soybean (Glycine max [L.] Merr.) Production Under Organic and Traditional Farming. In Environmental stresses in Soybean production (pp. 103-129). Academic Press.

Zhang, L., Spiertz, J.H.J., Zhang, S. 2008. Nitrogen economy in relay intercropping systems of wheat and cotton. Plant Soil, 303: 55–68

Zhang, L., van der Werf, W., Zhang, S., Li, B. and Spiertz, J.H.J. 2007. Growth, yield and quality of wheat and cotton in relay strip intercropping systems. Field Crops Research, 103: 178–188.

Zhang, W. P., Gao, S. N., Li, Z. X., Xu, H. S., Yang, H., Yang, X. and Li, L. 2021. Shifts from complementarity to selection effects maintain high productivity in maize/legume intercropping systems. Journal of Applied Ecology, 58(11): 2603-2613.

Zhou, T., Du, Y., Ahmed, S., Liu, T., Ren, M., Liu, W. and Yang, W. 2016. Genotypic differences in phosphorus efficiency and the performance of physiological characteristics in response to low phosphorus stress of soybean in southwest of China. Frontiers in Plant Science, 7: 1776.