Chapter

Integrated Pest Management in Cotton

Mirza Abdul Qayyum, Shafqat Saeed, Waqas Wakil, Muhammad Yasin, Ahmad Nawaz, Abid Ali, Habib Ali, Unsar Naeem-Ullah, Umer Sharif, Hasan Taha, Aiman Khalid, Iqra Maryum, Zeeshan Shahid and Wania Hasan Zubairi

Abstract

Cotton, one of the most important crops in the world, is threatened by a wide range of pests that lower both yield and quality. Integrated Pest Management (IPM) has come to be a comprehensive and eco-friendly method to tackle these issues while decreasing the need for synthetic pesticides. The first section of this chapter gives a general review of cotton as an essential agricultural commodity and its significance to the textile industry. After that, it explores the origins and evolution of IPM, providing an in-depth understanding of its concepts and the necessary elements needed to successfully apply it to cotton cultivation. Biological control, cultural practices, chemical control, host plant resistance, and other pest management strategies covered by Integrated Pest Management (IPM) are highlighted, along with how best to integrate them for maximum efficacy. Use of technology (Artificial intelligence) in early identification and detection of pest is necessary because it can help in timely decision making for pest management. Analyzing the ecological effects of IPM also gives information on how to reduce the amount of chemicals in cotton fields and preserve beneficial fauna. It is an important tool for farmers, academics, and policymakers who want to increase cotton profitability and long-term viability while reducing its negative effects on the environment and encouraging a stronger agricultural ecosystem.

Keywords: sustainable cotton production, integrated pest management, cotton insect pests, sucking pests of cotton, chewing pests of cotton

1. Introduction

1.1 Importance of sustainable cotton production

Although the manufacturing of synthetic fibers has risen, cotton continues to be the most significant fiber crop due to its global importance, garnering it the nickname "Queen of the Fiber Plants." Cotton production is a major industry in more than 80 nations, accounting for 2.5% of all cultivated land worldwide. Cotton also has commercial worth because it is essential to its producers' ability to earn foreign currency [1, 2]. Because of improvements in farming practices and the development of the industry for manufacturing products made of cotton, a significant portion of the nation's workforce—roughly 40% of all workers—have jobs thanks to the cotton industry. Another source of edible oil that contributes about 60% of the total amount consumed is cotton seed [3]. Although cotton is a natural fiber, modern cotton products do not merit the name "natural fiber" due to the increased consumption of synthetic pesticides and fertilizers (applied to nearly 99% of cotton crops) to increase crop yields and improve industrial production.

More than 230 different insect species have been recorded attacking cotton crops worldwide [4]. Since cotton is the most widely grown crop and is also more likely to be attacked by insect pests, it is discovered that 16% of all pesticides used worldwide are used on a single cotton crop. Agrochemicals make up about 50% of the overall cost of seed cotton production worldwide [5]. The ecosystem and environment are being negatively impacted by the widespread use of hazardous pesticides and chemicals. As more and more pesticide-resistant species appear and change insect patterns, the widespread use of chemicals disturbs the biological equilibrium. All of this contributed to an increase in production costs. Due to the fact that these chemicals are released into the air and water, they also reduce biodiversity by causing pollution [6]. The answer to all new issues is organic cotton. In other words, no inorganic fertilizers, herbicides, insecticides, or fungicides are used when growing cotton; it is instead grown naturally. It has certification from a recognized certifying body.

The use of fungicides and pesticides is decreased in organic production systems to a level that supports a variety of life forms, preserving biological diversity in agriculture. This aids in both replenishing and preserving soil fertility. Other names for organic cotton include "natural cotton," "clean cotton," "green cotton," or "environmentally friendly cotton". In contrast to traditional agricultural techniques, which place a big emphasis on using chemicals, organic cotton production systems use biological materials. Chemical fertilizers are prohibited for the growth of organic cotton and must be substituted with organic manure, such as gypsum, cotton seed meal, fish meal, cake, leather meal, farmyard and green manure, composite, etc. Additionally, botanical herbicides and insecticides like ipomea, neem cake, etc., are frequently utilized. Conventional cotton farming uses pesticides, insecticides, and herbicides that have been chemically synthesized.

When picking organic cotton, the use of chemical defoliants is also avoided [7]. Organic cotton fabric is substantially more expensive because its output is less than that of conventional cotton. Because no hazardous chemicals are allowed in the production of organic cotton, not only do farmers benefit from a healthy environment, but environmental contamination is also avoided. Considering that chemicals do not alter the makeup of soil, they continue to be fertile. The use of simple, nontoxic dyes rather than dangerous chemicals like chlorine, toxic finishes, bleach, etc., during organic treatment processes reduces the need to treat water that has been contaminated with chemicals during cotton production [8].

2. Need for effective crop management and processing practices

Alternating the soil and water, as well as increased chemical use, such as that of pesticides and fertilizers, is having an impact on life as we realize it. In children, methemoglobinemia (blue baby syndrome) is a disease caused by nitrates, which originate from nitrogen fertilizers. In California, the amount of volatile organic compound (VOC) emissions has risen to 11 million pounds, and disorders linked to pesticides are now the third most common. Recently, 13 insecticides that kill birds have been registered for use on cotton. The most hazardous result of utilizing these herbicides is that fish and other wildlife cannot reproduce [9].

Environmental protection, financial success, and social and economic equality are the three objectives of sustainable agriculture. In this context, it is important to preserve and improve land and natural resources while also taking into account consumer safety, health, and work conditions for farmers, as well as rural residents' wants and expectations. Sustainable crop production adheres to methods that respect human rights, the environment, and local and rural populations while also raising crops in an ethical and ecological manner. Sustainable crop management is centered on agricultural practices that are maintained over an extended period of time with little or no impact on the environment.

2.1 Soil management

Organic farming demands healthy soil. The soil serves as both a medium for plant growth and a living system that maintains the soil's health and productivity. Compost, effective nutrient recycling, cover crops, and regular crop rotation can all substitute for synthetic fertilizers [10].

2.2 Weeds management

Hoes and other mechanical tools, crop rotation, effective irrigation water usage, intercropping, the use of mulches, modifying plant densities, and adjusting panting dates can all be used to restrict the growth of weeds [11].

2.3 Insect pest management

Farmers can decrease the probability of insects and harm to crops caused by birds or mammals, a variety of living things. Insect predators and crop rotate your crops, use biological pesticides like neem oil, and Pests can be managed by intercropping by the cultivators [12]. There are seven essential conditions that must be maintained in order to effectively combat pests. In that sequence, the following are listed: (i) diagnosis, (ii) combat plan, (iii) timing of application, (iv) choice of pesticide, (v) choice of instrument, (vi) application, and (vii) supervision [13]. When these are applied in the management's order throughout a plant protection process, success is quite likely to occur.

2.4 Harvesting

Particularly in developing nations, organic cotton is typically harvested by hand without the use of machines, chemicals, or defoliants, which minimizes waste.

3. Issues in sustainable cotton production

3.1 Runoff from fields

When agricultural land's surface is fully saturated and unable to absorb additional water, it is said to have an excess of water. Runoff is the phrase used to describe this water's flow to nearby bodies of water. Runoff, which not only transports extra water but also contains pesticide, fertilizer, and salt residues that were applied to the cotton crop, is caused by a variety of factors, including improper water management and inexperience with irrigation [14].

3.2 Drainage and leaching

Salinity in irrigation or soil is a significant issue for cotton farming. It affects crops' access to soil water and is comparable to water scarcity. Cotton can keep out sodium ions and is salinity resistant. As a result, there is a chance that issues will not be recognized until they have accumulated.

4. Crop management practices

4.1 Selection of suitable cotton varieties

The choice of seeds is made in accordance with the soil and climate conditions, farming methods, and estimated yields [15]. For mechanical drilling, 20–30 kg/ha of seed is needed, whereas 14–16 kg/ha is needed for ridge sowing [16]. The chosen seed should be able to withstand extremes in temperature as well as very low ones [17]. It should also be resistant to diseases like CLCuV and able to survive droughts [18]. The cotton varieties (CYTO 177, FH 326, BS 15, Sahara 120, Weal AG Shahkar, NIAB 878, Tarzan 3, NIABG 4, CYTO 179, CIM 600, and BPC 11) that Punjab Seed Council just issued have resistance for a variety of diseases and insect pests.

4.2 Seed treatment

The cotton seeds frequently have low germination rates. To increase germination, cotton seed is cleaned of lint [19]. Acid delinting and mechanical removal are the two processes that are most commonly employed to remove lint from cotton seed. For seed delinting, sulfuric acid and hydrochloric acid are frequently employed [20]. The heat created by the acid and moisture interaction causes the short fibers on cotton seeds to deteriorate [21]. Water is used to wash the residue. The wet acid technique, which uses soda ash or ammonia to neutralize the seed lime, is so named [22]. Fungicides are used in the treatment of delinted seed.

4.3 Sowing time

The season for planting cotton begins in April and lasts through the end of May [23]. The quality of cotton fiber is impacted by late planting. Cotton planting may begin in May in warm places (mainly in the south). To investigate a cultivar's production potential in each area, the date of planting is crucial [24]. Warm soil temperatures are necessary for cotton seed germination because they promote strong seedling growth [25]. Low soil temperature, which causes poor plant development, makes crops seeded very early, particularly in the month of February, appear to have a weak crop stand [26]. Similarly, cotton seedlings planted too late are shaded by weeds [27].

Weed infestation, CLCuV infection, and heat stress all limit crop development [28]. Any inadequate management of cotton that was planted in the late season reduces production. Accordingly, the planting date is a crucial determinant in the potential production and healthy plant growth [29].

5. Land preparation and fertility management

5.1 Land preparation

To guarantee uniform planting depth, cotton needs a surface of soil with a very fine tilth and a smooth texture [30]. To achieve a sufficient plant stand, several field operations are required. A deep soil is necessary for healthy root growth since cotton is a crop with deep roots [31]. Land needs to be clear of clods and stubble. Cotton should be deep-plowed at least four times, followed by two planks to make the soil fine, loose, and level in order to get the best possible germination and development [32]. When Pakistani cotton farmers use a tractor to plow their fields, the earth is torn up to 15 cm deep [33]. In comparison to compacted soil, root hairs often functioned better in uncompacted soil. Due to compacted soil's decreased ability to absorb vital nutrients and water, root development slows down, and root hair function is poor [34]. After rigorous plowing, cotton is successfully sown on ridges [35].

5.2 Fertilization

The amount of fertilizer needed for cotton varies on the soil type, weather, and variety of the crop [36]. For various types of soil, there are different needs. According to a countrywide soil investigation, deficiencies of nitrogen (N), phosphorus (P), and rarely potassium (K) have been noted [37]. It is advised to apply 200 kilograms N, 145 kg P, and 95 kg K per ha to poor soils. N and K dosages for medium and rich soils are the same, while P requirements are 114 and 87 kg/ha, respectively [38]. Due to their early fruiting habits, current early cotton cultivars respond well to the use of N fertilizers. In earlier investigations, cotton cultivars were shown to respond favorably to N and P fertilizers [39].

Taller varieties need less N because of their strong root systems. According to soil testing results, farmers must apply zinc (Zn) and boron (B) at rates of 12 and 9 kg/ha, respectively, in the majority of Pakistan's cotton-growing regions [40]. When sowing, a baseline dosage of the major nutrients like P and K as well as the minor nutrients like Zn and B should be applied [41]. N should be applied in accordance with the crop's requirements and the local climate at the time [42]. In this study, 30 kgN per hectare should be administered once a week for 3 weeks straight in the situation that leaf curl virus symptoms develop [43].

6. Water management

A greater yield is a product of adequate irrigation since it keeps water circulating to the plant's roots and dilutes the vital micro and macronutrients that support healthy plant growth [44]. Salts accumulate in the root zone as a result of insufficient watering, and the plants have little access to nutrients [45]. In contrast, excessive irrigation raises the water table, which pushes salts higher and prevents plants from performing their physiological activities properly since there is insufficient carbon dioxide available to the root zone [46]. The crop's health, the weather, and the sowing technique should all be taken into consideration while scheduling irrigation [47]. A flat-sown crop receives its initial watering 35–40 days after planting, and following irrigations are spaced 12–15 days Apart [48].

By the first 10 days of October, the final irrigation for this type of seeding should have been given [49]. To ensure adequate germination when using the bed planting method, the initial watering should be administered 3–4 days after sowing [50]. Depending on the crop condition and variety, the second and third irrigations should be applied weekly, and the remaining irrigations should be applied every 15 days [51]. To prevent excessive vegetative growth during the wet season, irrigation should be done judiciously [52]. The bed planting method's irrigation termination date is October 15 to allow for the timely sowing of the wheat crop [53].

7. Pest and disease management

One of the main barriers to Pakistani cotton production is insect infestations [54]. The main obstacles to Pakistan's high cotton productivity are sucking insects (including whiteflies, jassids, and aphids) and bollworms (such as the American bollworm, spotted bollworm, and pink bollworm) [55]. The farmers' efforts to manage these insect pests are occasionally hampered by untimely rains and high temperatures, which cause crop losses and significant output decreases [56]. Even with substantial pesticide treatment, farmers were unable to manage the heavy whitefly attack throughout the months of June, July, and August, which led to the loss of cell sap, low boll setting, and low crop output in all cotton-growing regions [57].

Whitefly infestations were severe, which helped CLCuV spread in Punjab's hotspot regions and contributed to poor cotton production [28]. Similar to this, during October's high temperatures and poor Bt variety expression, pink bollworms spread and damaged bolls, resulting in a low cotton yield [58]. Bt (Cry1Ac) gene's low expression after 80 days has reduced its efficiency, making it inappropriate to protect cotton from various bollworms [59]. Although there is currently no scientific evidence, it is possible that some pink bollworm pests with high levels of resistance might migrate from India. The resistant pest may have been transported through the import of Indian cotton and the quarantine department's lack of action [60].

High temperatures during blooming and boll development are yet another major barrier to Pakistan's cotton output [61]. This causes blooms and bolls to fall off, which affects crop yields and output across the nation. Among the cotton diseases, CLCuD caused by several CLCuV (Begomovirus) strains has continued to be a major barrier to Pakistan's ability to produce cotton [62]. The prevalence of this disease is declining in the nation as a result of evolution, where cultivars have a high degree of tolerance against CLCuV [28]. However, in recent years, bacterial cotton blight has started to bring a serious danger to cotton output [63].

Other significant factors contributing to low cotton productivity include poor soil productivity, insufficient fertilizer use, salinity, waterlogging, insufficient water supply, improper soil and water management, pesticide misuse, early or late cotton planting, division between landlords and tenants, low adoption of new technology, financial constraints, and low literacy levels [36, 64].

8. Weed control

Due to weeds' competition for resources including water, light, nutrients, and space, weeds can seriously harm cotton output [65]. Weeds' sluggish appearance and development rates make cotton particularly vulnerable to them [66]. *Amaranthus viridis* L., *Portulaca oleracea* L., *Convolvulus arvensis* L., *Digera arvensis* Forssk., *Xanthium strumariun* L., *Cyperus rotundus L.*, *Echinochloa colona* (L.) Link, and *Cynodon* *dactylon* (L.) Pers. is among the common cotton weeds in Pakistan [40]. In the first 60 days of crop growth, these weeds are the most damaging because, in addition to contributing to low output owing to the sharing of crop nutrients, they can also act as a secondary home for pests and viruses that affect cotton [67].

Pre-emergence herbicides such pendimethalin or S-metolachlor, which can control the weeds for at least 35–40 days after planting, must be used to control the weeds at the early stage [68]. Post-emergence herbicides including haloxyfop-R-methyl, fluazifop-P-butyl, and quizalofop-p-ethyl have been given permission to be used to manage weeds in cotton [69]. Weeds are eradicated after reemergence either manually or with the help of recently imported Chinese mini-hoeing devices [70]. The majority of farmers combine the use of pesticides with mechanical weed management to effectively control weeds [71]. It is necessary to continue the weeding procedure until the plants form a canopy that shadows the weeds and inhibits their development [72].

9. Criteria for sustainable cotton production

The criteria for sustainable cotton production may vary depending on the certification program or standard being followed. However, here are some common criteria and practices often considered in sustainable cotton production:

1. Environmental Criteria:

    - Reduced Chemical Use: Minimizing the use of synthetic fertilizers, pesticides, and herbicides, and promoting Integrated Pest Management practices.

    - Water Conservation: Efficient irrigation methods, water recycling, and reducing water consumption.

    - Soil Health: Promoting soil fertility, conservation, and erosion control through practices such as crop rotation and cover cropping [73].

    - Biodiversity Conservation: Preserving and enhancing biodiversity on cotton farms by protecting natural habitats and wildlife.

2. Social Criteria:

    - Fair Labor Practices: Ensuring safe and fair working conditions, fair wages, and adherence to labor laws and standards.

    - Workers' Rights: Respect for the rights of workers, including freedom of association, no child or forced labor, and non-discrimination.

    - Community Engagement: Supporting local communities through capacity building, education, healthcare, and infrastructure development.

3. Traceability and Transparency:

    - Documented Supply Chain: Maintaining a transparent and traceable supply chain from farm to final product, allowing for verification and accountability.

- Certification and Auditing: Regular audits and inspections to ensure compliance with sustainability standards and practices.

4. Resource Efficiency:

- Energy Conservation: Promoting energy-efficient practices in farming operations, processing, and transportation.
- Waste Management: Proper handling and disposal of waste, recycling, and reducing waste generation.

5. Continuous Improvement:

- Farmer Training and Support: Providing farmers with education, training, and access to resources to enhance their knowledge and skills in sustainable practices.
- Research and Innovation: Encouraging research and development of sustainable farming techniques and technologies to improve cotton production practices.

It is important to note that the specific criteria and weightage assigned to each criterion may vary among different certification programs. Farmers and cotton industry stakeholders are encouraged to adopt these sustainable practices to reduce the environmental impact of cotton production and promote social responsibility within the supply chain [74].

9.1 To address these challenges, potential solutions include

1. Farmer Support and Capacity Building: Providing training, technical assistance, and access to resources for farmers to adopt sustainable practices and meet certification requirements. This can be achieved through partnerships with local organizations, governments, and industry stakeholders [75].
2. Financial Incentives: Offering financial support, incentives, or premium prices for certified cotton to offset the costs associated with certification and encourage adoption among farmers [76].
3. Collaboration and Partnership: Building strong partnerships and collaborations among stakeholders in the cotton supply chain, including farmers, brands, retailers, and certification bodies. Working together can streamline processes, improve communication, and share knowledge and resources [77].
4. Technology and Data Management: Leveraging digital technologies, such as blockchain and digital platforms, to enhance traceability, data management, and transparency in the cotton supply chain. This can improve supply chain efficiency and facilitate verification processes [78].
5. Consumer Education and Awareness: Investing in consumer education and awareness campaigns to increase understanding of certified cotton and its

benefits. Providing clear and easily recognizable labels and marketing materials that highlight the sustainability credentials of certified cotton can help consumers make informed choices [79].

Addressing these challenges requires a multi-stakeholder approach, with active involvement and collaboration among farmers, industry players, certification bodies, governments, and civil society organizations. By addressing these challenges, cotton certification programs can enhance their effectiveness, increase adoption rates, and drive sustainable practices throughout the cotton supply chain.

10. Case study successful implementation

10.1 Case study: successful integration of sustainable practices in a cotton chain

The textile and clothing (T&C) business plays a crucial role in people's daily lives, and the products it produces are regarded as the second-most important thing that people desire. The sector has grown significantly and achieved great success over the past few decades, making it one of the most significant but also most polluting worldwide industries [80]. Significant environmental and social effects are caused by its magnitude, diversity of processes, and intricate worldwide production networks. Three natural fibers have been used by humans for at least 5000 years each: flax, wool, and cotton.

Today, 48% of all textiles are made from cotton. Only 27% of cotton is grown in rain-fed conditions globally, with irrigated fields accounting for the majority (73%). According to [81], irrigated cotton has an average output of 845 kg per hectare, and rain-fed cotton has an average yield of 391 kg per hectare. 75% of the total global production of cotton is produced by the six biggest cotton-producing nations (China, USA, India, Pakistan, Uzbekistan, and Turkey). Over the past 40 years, the contemporary cotton business has made substantial environmental progress, but it is not letting up.

Researchers and scientists work to create innovative techniques that will enable cotton to be grown, processed and manufactured more effectively and with less environmental impact. The cotton industry will be able to fulfill the demands for productivity and profit while identifying and implementing innovative technologies and practices without sacrificing the ability of future generations to meet their own needs.

10.2 Collaboration among stakeholders

Businesses began signing up for these certification programs to expand their market share and take advantage of fresh opportunities and trends. At the same time, these programs give companies the chance to have more control over their supply chains, ensuring safety and quality requirements while lowering manufacturing costs [82]. Positive side effects of certification included improved reputation and confidence among consumers and other stakeholders.

According to Bolwig *et al*. [83], certification schemes and the methods employed to implement them determine the extent to which these desired beneficial results are realized. In order to enhance the environmental and social circumstances of production operations in developing nations, sustainable chain governance systems have emerged as a result of collaboration between various market and non-market players [84].

10.3 Training

Training farmers helps them become more productive, more able to meet the quality standards demanded by international supply chains, and more capable of producing food.

10.4 Information systems

Giving smallholders access to information and communications can assist them in making decisions and expanding into new or more advantageous markets. According to Parikh *et al*. [85], sound decision-making requires knowledge about the market. Adaptation of sustainable practices should be done at different stages.

Despite the fact that cotton contributes significantly to both national and rural economies, the extensive use of irrigation water, inorganic fertilizer, and pesticides has had a negative impact on the environment, public health, and financial return. Cotton with such significant external inputs and resource requirements is frequently referred to as conventional cotton. A similar innovation occurs in agriculture when a new crop, product, method, or approach to carrying out agricultural tasks is introduced. Innovations that improve sustainability from the perspectives of the economy, society, and environment are referred to as sustainable innovations.

10.5 Land use

In order to build a more sustainable future, agricultural land must be used effectively and efficiently. The good news is that cotton growers have implemented a number of techniques intended to maximize land use effectiveness, such as

1. Improving genetic variety and farmer management to increase cotton fiber production.

2. Encouraging crop rotation, no-till methods, and cover crops to improve soil health.

3. Using more advanced sensors and computer programs for irrigation scheduling.

4. Expanding precise applications through the use of geospatial technologies.

5. Using digital technologies to provide farmers more capacity for prediction.

6. Increasing farmer knowledge of soil health and putting strategies in place that foster a diversified and healthy rhizosphere.

10.6 Pesticides

Thanks to advancements in biotechnology and pest management, cotton growers may use a lot less pesticides and insecticides now than they did in the past. In actuality, cotton consumes an average of only five grams of pesticides per kilogram compared to other crops. The Boll Weevil Eradication Program, started in the 1970s, was one of the most successful uses of Integrated Pest Management in history. Boll weevils used to cost American farmers $300 million in crop damage per year; however, all states in the union that grow cotton have eradicated the pest entirely, with the exception of Texas.

Thanks to this innovative method, cotton growers have been able to cut their insecticide applications by 50 percent since the 1980s. Many of those that are still in use target specific species, protecting other organisms from damage and enabling them to continue existing and contributing to the ecosystem. Sustainable supply chain management, which coordinates demand needs toward suppliers along the supply chain while addressing economic as well as social and environmental issues, is strongly emphasized by corporate responsibility in global sourcing operations [86].

10.7 Positive impacts on environment and social aspects

Cotton is the most profitable and extensively cultivated non-food crop globally. Its manufacture generates income for over 250 million people and employs more than 7% of the labor force in underdeveloped countries. Approximately half of all textiles are made of cotton. Despite cotton's enormous worldwide market, the unsustainable nature of the current production techniques threatens the industry's capacity to continue producing the crop in the future. Bringing cotton production into compliance with even the most minimally acceptable environmental standards is a challenging task. To encourage the ethical production and use of cotton, WWF is working with a variety of international partners in various capacities. The three main environmental impacts of cotton are water use, habitat modification, and the use of agrochemicals, especially pesticides.

10.8 Water scarcity

Water is extensively used in the growth and processing of cotton. According to some experts, among all agricultural products, cotton uses the most water. To irrigate cotton crops, surface and ground fluids are frequently diverted, resulting in freshwater loss through evaporation and ineffective water management.

10.9 Soil erosion and degradation

Water is used a lot in the growth and processing of cotton. Out of all agricultural products, cotton is said to require the most water by certain specialists. Frequent diversion of surface and groundwater for cotton crop irrigation results in freshwater loss due to evaporation and ineffective water management.

10.10 Pollution

Conventional cotton farming practices involve heavy use of pesticides and fertilizers. Pesticides endanger not only the water and soil quality but also the biodiversity in and around the fields. Because pesticides are used so extensively, there is also concern for the health of farm workers and the neighboring populations.

10.11 Water contamination

Pesticides, fertilizers, and minerals are introduced into rivers, lakes, marshes, and subsurface aquifers by cotton field runoff. Because of their rapid toxicity, these pollutants either directly or indirectly destroy biodiversity through long-term accumulation.

11. Future directions and conclusions

11.1 Technological developments for the sustainable production of cotton

The implementation of these key technologies is required to attain sustainable cotton production.

11.1.1 Single-seed precision sowing technology

High-quality finishing seeds, meticulous soil preparation, a sensible row spacing arrangement, mechanical seeding, and no thinning or final singling of seedlings after emergence are all part of the single-seed precision sowing method for cotton. High-quality finishing seeds, meticulous soil preparation, a sensible row spacing arrangement, mechanical seeding, and no thinning or final singling of seedlings after emergence are all part of the single-seed precision sowing method for cotton. This method also does away with the need for planting, thinning, and final singling.

11.1.2 Light and simplified seedling nursery technology

A novel method called light and simple nursery and transplanting of cotton seedlings is intended to replace the conventional matrix and water floating seedling nurseries, as well as traditional nutrition bowl nursery and transplanting. The general protocol of conventional nutrition bowl nurseries and transplanting is followed by these nursery techniques. To create an industrial nursery, they replace ordinary soil with commercial matrices (combinations of peat, vermiculite, and river sand) or nutrient solutions combined with chemicals that promote root development, preserve leaves, and control other aspects of plant growth. The number of seedlings per unit area rises as a result of the alternative to the common soil, and cotton seedlings with little or no soil are utilized for transplanting. Additionally, the use of machinery for cotton seedling transplantation guarantees mechanized transplanting, lowers labor intensity, and increases productivity. In light of this, the new technology for cotton seedling nursery and transplanting is somewhat lighter and simpler than the conventional methods.

11.1.3 One-time fertilization technique

The three main cotton-growing regions of China rely on light, easy, and effective fertilization, with the amount of fertilizer used determined by the output of the cotton. The appropriate amount is 225–240 kg/ha for high-yield fields with an area of 3750 kg/ha or higher, and the $N:P_2O_5:K_2O$ ratio is roughly 1.0:0.6:0.7–0.9. The yield of seed cotton in the northwest inland cotton area is between 4500 and 5250 kg/ha, and 280 to 330 kg/ha of N is the appropriate amount. The $N:P_2O_5:K_2O$ ratio is roughly 1.0 0.5:0-0.3, and it can be decreased by 15% by integrating water fertilizer. The other is lowering the frequency of fertilization by applying cotton special slow-release fertilizer. The Yangtze River Valley cotton area uses a one-time basal application of controlled or slow-release fertilizer; 10–20% less slow-release fertilizer can be equivalent to the standard fertilization dosage.

11.1.4 Water and fertilizer integration technology

Optimizing water efficiency during irrigation is the goal of cotton water-saving irrigation technology. The most popular water-saving irrigation system that combines surface drip irrigation and plastic film mulching is drip irrigation under plastic mulching, which is extensively utilized in the northwest inland region. It supplies water via a low-pressure pipeline system, filters the pressurized water using filter facilities, and dissolves the fertilizer in water to create an aqueous solution. To keep the concentrated cotton root regions at the proper moisture content for the incorporation of water and fertilizer, this solution permeates them uniformly. The average water consumption for sprinkler irrigation is 50%, compared to 12% for traditional irrigation. The amount of fertilizer needed is lowered by 15–20%.

12. Research and development priorities

Under the guidance of PCCC, three cotton research institutions and seven research stations collaborate to improve cotton output. Several experimental research and development initiatives aid in identifying bottleneck problems for the production of sustainable cotton. Multidisciplinary research at the Central Cotton Research Institutes (CCRI) at Sakrand, Sindh, and Multan, Punjab, has greatly aided in the development of improved cultivars. Moreover, CCRI Multan controls germplasm resource distribution, identification, evaluation, maintenance, and preservation. Moreover, the primary government institutions that carry out research on numerous cotton-related themes are Bahauddin Zakariya University (BZU), Islamia University Bahawalpur (IUB), University of Agriculture Faisalabad (UAF), and Mohammad Nawaz Shareef University of Agriculture, Multan (MNS-UAM). Through the planning of several workshops, training sessions, and seminars, these organizations support the growing of cotton. Cotton breeding initiatives have been started by numerous recognized national and worldwide private commercial business companies in addition to state organizations. Their contribution to cotton research and development has been impaired, meanwhile, by a shortage of skilled breeding personnel, ineffective resources, and outdated breeding facilities.

12.1 Breeding for stress resilient cotton in Pakistan

a. Stress hazards, which are often classified as either biotic or abiotic, have a significant impact on cotton output. Abiotic stresses include heat, dryness, and salinity are examples of environmental conditions, whereas biotic stresses include pests, viruses, and fungal diseases. Plant growth was altered morphologically, physiologically, and biochemically as a result of the extended stress. Pakistan is a country where cotton is very susceptible to a variety of biotic and abiotic stressors, which combined reduce cotton yield and fiber quality. The yield per hectare and total cotton production have recently been negatively impacted by sucking insects, bollworms, cotton leaf curl virus, and extreme temperatures.

b. Biotic stress-resilient cotton: The production of cotton in Pakistan is severely declined due to attack of many chewing and sucking insect pest. Even after multiple Bt cultivars were introduced, the resistant cultivars are still being evaluated and are in the development stage. The cotton plant sustained major damage as a result of the severe bollworm invasion throughout the growth season. The main cause of the rise in pink bollworm in recent years is higher temperatures throughout September and October. The army bollworm's extreme invasion has a significant impact on cotton output. However, army worms' efficient management methods are still inadequate to eradicate huge populations at once. Therefore, creating resistance cultivars is the only practical way to manage bollworms and create Integrated Pest Management (IPM) plans. The cultivars CIM-499, CRIS-468, MNH-633, MNH-635, and MNH-886 have all been approved. Targeted genome editing may therefore be essential to creating cotton that is resistant to bollworms.

c. In cotton, sucking insects can diminish production by roughly 30–50%. In both Bt and non-Bt cotton cultivars, the mealy bug, dusky bug, jassid, and whitefly seemed to be the most common detrimental pests that drain the sap of the plant during the vegetative and reproductive stages. Various breeding strategies were employed to create cultivars of CLCuD resistance. During the first outbreak, the resistance of NIAB-846, NIAB-111, CIM-443, Bt-Cyto-178, Cyto-124, MNH-886, and FH-142 was better.

d. Abiotic stress-resilient cotton: Global warming is causing harm to the world's sustainable cotton production. Cotton production is adversely affected by abiotic conditions such as heat, drought, salt, and nitrogen shortage. In Pakistan, the cotton-producing season is typically characterized by high temperatures between 40 and 45 degrees Celsius. The cotton crop's potential output is limited by low or high temperatures. Cold temperatures during the seeding stage cause delayed germination and uneven crop establishment. [87]. Furthermore, the physiological, metabolic, and biochemical processes of boll formation, lint output, and fiber quality were all impacted by high-temperature stress. Prior research in breeding demonstrated the value of using bulk selection in conjunction with pedigree selection to produce heat-tolerant cultivars. The CIM-240, CIM-598, CIM-777, NIAB-999, NIAB-111, and CIM-602 exhibit superior adaptability to heat stress. Cotton is a moderately salt-tolerant plant, but the level of tolerance differs among genotypes [88]. It is more vulnerable to salt stress in the early stages of seedling emergence and germination. High salt content prevents the growth of roots and shoots, which eventually alters cotton output and fiber quality [89]. NIAB-78, FH-113, MNH-93, NIAB-999, and CIM-707 all showed improved salt tolerance when cultivated. However, the primary breeding problem facing the majority of Pakistani cotton producers remains the development of cultivars resistant to salt. To improve cotton output per acre, critical nutrients must be available. Cotton's growth was hampered by a substantial nutritional deficit. On the other hand, overnutrition has harmful consequences. Breeding in Pakistan is still restricted when it comes to genotypes that are highly input-responsive.

12.2 Marker-assisted breeding

- The effectiveness of traditional plant breeding operations has greatly increased with the latest developments in molecular markers. Linkage maps are frequently created using various molecular markers in order to identify quantitative trait loci (QTLs). Cotton markers include:

- Simple sequence repeats (SSRs).
- Single nucleotide polymorphism (SNP).
- Amplified fragment length polymorphism (AFLP).
- Random Amplified Polymorphic DNA (RAPD).

shown to be beneficial for investigating genetic diversity, genetic mapping of desired phenotypes, determining candidate gene nucleotide sequences and assisting with marker-assisted breeding (MAS). There has been significant progress in identifying QTLs related to agronomic traits, yield components, fiber quality, plant architecture, leaf trichomes, leaf pubescence, seed oil, seed gossypol contents, early maturity, heat tolerance, drought tolerance, salt tolerance, and disease resistance thanks to QTL mapping using a suitable cotton mapping population. In Pakistan, NIBGE-2 and NIBGE-115 were bred using a combination of traditional methods and DNA markers linked to resistance to the cotton leaf curl viral disease. Likewise, MAS was used to produce the resistance genotypes CIM-443 and CIM-240 against the cotton leaf curl viral disease. The CRIS-134 cultivar was found to have a variety of QTLs for drought tolerance when MAS was applied to it. In the meantime, Pakistan's widespread application of molecular markers for MAS is still in its infancy.

13. Conclusion and key take away

About 1.7 million people in Pakistan are involved in the value chain of cotton farming. Pakistan ranks fourth globally in terms of the amount of cotton lint produced. Nowadays, a multitude of biotic and abiotic variables provide numerous obstacles for cotton. Biotic variables, which are major contributors to the decline in cotton yield, include weeds, illnesses, and insect pests. Weeds and pest insects that feed on nectar are major problems in the beginning. Using pesticides is not the only approach to managing insect infestations. Starting with the selection of seed kinds resistant to pest insects is the right course of action. Every element, including fertilizer use and irrigation, contributes to the proliferation of pests. The attack of sucking insect pests is increased when nitrogenous fertilizers are used excessively. It is advisable to promote the use of green lacewing and ladybird beetles to reduce the number of sucking pests, such as whiteflies and jassids. Various management techniques are used depending on the type of insect problem.

Author details

Mirza Abdul Qayyum[1]*, Shafqat Saeed[1], Waqas Wakil[2], Muhammad Yasin[3], Ahmad Nawaz[4], Abid Ali[2], Habib Ali[5], Unsar Naeem-Ullah[1], Umer Sharif[1], Hasan Taha[1], Aiman Khalid[1], Iqra Maryum[1], Zeeshan Shahid[1] and Wania Hasan Zubairi[1]

1 Institute of Plant Protection, MNS University of Agriculture, Multan, Pakistan

2 Department of Entomology, University of Agriculture, Faisalabad, Pakistan

3 Department of Entomology, Islamia University Bahawalpur, Pakistan

4 Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Oman

5 Department of Entomology, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

*Address all correspondence to: qayyum.mirza@mnsuam.edu.pk

References

[1] Abbas HG, Mahmood A, Ali Q. Zero tillage: A potential technology to improve cotton yield. Genetika. 2016;**48**(2):761-776

[2] Goldbach M, Seuring S, Back S. Co-ordinating sustainable cotton chains for the mass market. Greener Management International. 2003;**43**:65-78

[3] Zia SM, Inayatullah C, Samee M, Hasnain T. Sustainable Cotton Production, Trade and Environmental Impact: Policy Issues and Options for Pakistan. Pakistan: Sustainable Development Policy Institute; 1998

[4] Brader L. Integrated pest control in the developing world. Annual Review of Entomology. 1979;**24**(1):225-254

[5] Chapagain AK, Hoekstra A, Savenije H, Gautam R. The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecological Economics. 2006;**60**(1):186-203

[6] Josipović M, Plavšić H, Kovačević V, Marković M, Iljkić D. Impacts of irrigation and genotype on yield, protein, starch and oil contents in grain of maize inbred lines. Genetika. 2014;**46**(1):243-253

[7] Khaliq A, Abbasi MK, Hussain T. Effects of integrated use of organic and inorganic nutrient sources with effective microorganisms (EM) on seed cotton yield in Pakistan. Bioresource Technology. 2006;**97**(8):967-972

[8] Myers D, Stolton S. Organic Cotton: From Field to Final Product. London, U.K: Intermediate Technology Publications Ltd (ITP); 1999

[9] Luz C. Waste couture: Environmental impact of the clothing industry. Environmental Health Perspectives. 2007;**115**(9):A448

[10] Muthu SS. Roadmap to sustainable textiles and clothing: Eco-friendly raw materials, technologies, and processing methods. New York, Dordrecht, London: Springer; 2014

[11] Elahi M, Cheema S, Basra MA, Ali Q. Use of Allelopathic water extract of field crops for weed control in wheat. International Research of Journal of Plant Science. 2011;**2**(9):262-270

[12] Husnain T. Transformation and transgenic expression studies of glyphosate tolerant and cane borer resistance genes in sugarcane (*Saccharum officinarum* L.). Molecular Plant Breeding. 2015;**6**(12):1-17

[13] Singh K, Singh H, Singh K. Weed management in cotton with pre-and post-emergence herbicides. Indian Journal of Weed Science. 2016;**48**:348. DOI: 10.5958/0974-8164.2016.00090.3

[14] Choudhury AR. Development of Ecolabels for Sustainable Textiles: Roadmap to Sustainable Textiles and Clothing. Springer; 2015. pp. 137-173

[15] Ali A, Hussain T, Tantashutikun N, Hussain N, Cocetta G. Application of smart techniques, internet of things and data mining for resource use efficient and sustainable crop production. Agriculture. 2023;**13**(2):397

[16] Ali H, Hussain GS, Hussain S, Shahzad AN, Ahmad S, Ahmad HMR, Sarwar N. Early sowing reduces cotton leaf curl virus occurrence and improves cotton productivity.

Agronomical Research in Moldavia/ Cercetări Agronomice în Moldova. 2014;**60**(4):71-81

[17] Hou QQ, Chen BM, Peng SL, Chen LY. Effects of extreme temperature on seedling establishment of nonnative invasive plants. Biological Invasions. 2014;**16**:2049-2061

[18] Sufyan Tahir M, Latif A, Bashir S, Shad M, Khan MAU, Gul A, et al. Transformation and evaluation of broad-spectrum insect and weedicide resistant genes in *Gossypium arboreum* (Desi Cotton). GM Crops & Food. 2021;**12**(1):292-302

[19] Karaca M, Ince AG. A DNA extraction method for nondestructive testing and evaluation of cotton seeds (*Gossypium* L.). Biochemical Genetics. 2023. DOI: 10.1007/s10528-023-10496-5

[20] Antneh DN. Effect of dosage and duration of sulfuric acid on delinting, seed germination and seedling vigor of cotton (*Gossypium hirsutum L.*) [Doctoral dissertation]; Department of Plant Sciences, College of Agriculture and Rural Transformation, University of Gondar); 2017

[21] Xu B, Gao M, Hu W, Zhao W, Wang S, Zhou Z. Individual and interactive influences of elevated air temperature and soil drought at the flowering and boll-forming stage on cottonseed yield and nutritional quality. The Crop Journal. 2022;**10**(1):128-139

[22] Lima JME, Carvalho ER, Moraes LFDS, Cossa NHDS, Miquicene FVC, Gradela YF. Delinting and neutralizers residue effect on stored cotton seeds physiological quality determined by phenotyping image analysis. Journal of Seed Science. 2023;**45**:e202345014

[23] Paz JO, Woli P, Garcia AGY, Hoogenboom G. Cotton yields as influenced by ENSO at different planting dates and spatial aggregation levels. Agricultural Systems. 2012;**111**:45-52

[24] Mudassir MA, Rasul F, Khaliq T, Yaseen M. Conformance of sowing dates for maximizing heat use efficiency and seed cotton yield in arid to semi-arid cotton zone of Pakistan. Environmental Science and Pollution Research. 2021;**19**:1-15

[25] Dong H, Li W, Tang W, Zhang D. Furrow seeding with plastic mulching increases stand establishment and lint yield of cotton in a saline field. Agronomy Journal. 2008;**100**(6):1640-1646

[26] Hollinger SE, Angel JR. Weather and crops. In: Illinois Agronomy Handbook. 2009. pp. 1-12

[27] Fernando M, Shrestha A. The potential of cover crops for weed management: A sole tool or component of an integrated weed management system? Plants. 2023;**12**(4):752

[28] Farooq J, Farooq A, Riaz M, Shahid MR, Saeed F, Iqbal MS, et al. Cotton leaf curl virus disease a principle cause of decline in cotton productivity in Pakistan (a mini review). Canadian Journal of Plant Protection. 2014;**2**:9-16

[29] Constable GA, Bange MP. The yield potential of cotton (*Gossypium hirsutum* L.). Field Crops Research. 2015;**182**:98-106

[30] McDonald MF, Copeland LO. Seed Production: Principles and Practices. Springer Science & Business Media; 2012

[31] Katsvairo TW, Wright DL, Marois JJ, Hartzog DL, Balkcom KB, Wiatrak PP,

et al. Cotton roots, earthworms, and infiltration characteristics in sod–peanut–cotton cropping systems. Agronomy Journal. 2007;**99**(2):390-398

[32] Singh K, Mishra SK, Singh M, Singh K, Brar AS. Water footprint assessment of surface and subsurface drip fertigated cotton-wheat cropping system–a case study under semi-arid environments of Indian Punjab. Journal of Cleaner Production. 2022;**365**:132735

[33] Raza W, Yousaf S, Niaz A, Rasheed MK, Hussain I. Subsoil compaction effects on soil properties, nutrient uptake and yield of maize fodder (*Zea mays* L.). Pakistan Journal of Botany. 2005;**37**(4):933

[34] Haling RE, Brown LK, Bengough AG, Young IM, Hallett PD, White PJ, et al. Root hairs improve root penetration, root-soil contact, and phosphorus acquisition in soils of different strength. Journal of Experimental Botany. 2013;**64**(12):3711-3721

[35] Accorsi E. Tape your way to sustainability: A Life Cycle Assessment of a sport tape made from conventional cotton and ways to minimize its environmental impact [Doctoral dissertation]; Politecnico di Torino; 2023)

[36] Khan A, Tan DKY, Afridi MZ, Luo H, Tung SA, Ajab M, et al. Nitrogen fertility and abiotic stresses management in cotton crop: A review. Environmental Science and Pollution Research. 2017;**24**:14551-14566

[37] Ryan J, Rashid A, Torrent J, Yau SK, Ibrikci H, Sommer R, et al. Micronutrient constraints to crop production in the Middle East–West Asia region: significance, research, and management. Advances in Agronomy. 2013;**122**:1-84

[38] Ullah A, Ahmad I, et al. Optimizing management options through empirical modeling to improve pearl millet production for semi-arid and arid regions of Punjab, Pakistan. Sustainability. 2020;**12**(18):7715

[39] Shahzad AN, Rizwan M, Asghar MG, Qureshi MK, Bukhari SAH, Kiran A, et al. Early maturing Bt cotton requires more potassium fertilizer under water deficiency to augment seed-cotton yield but not lint quality. Scientific Reports. 2019;**9**(1):7378

[40] Ali MA, Farooq J, Batool A, Zahoor A, Azeem F, Mahmood A, et al. Cotton production in Pakistan. Cotton Production. 2019:249-276

[41] Seleiman MF, Al-Suhaibani N, El-Hendawy S, Abdella K, Alotaibi M, Alderfasi A. Impacts of long-and short-term of irrigation with treated wastewater and synthetic fertilizers on the growth, biomass, heavy metal content, and energy traits of three potential bioenergy crops in arid regions. Energies. 2021;**14**(11):3037

[42] Rigby H, Clarke BO, Pritchard DL, Meehan B, Beshah F, Smith SR, et al. A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emissions to the environment. Science of the Total Environment. 2016;**541**:1310-1338

[43] Dingus A. Characterizing Fonio production across scales: Interdisciplinary insights from a local field trial and a scoping review [Doctoral dissertation]; Michigan State University. 2022

[44] Roy RN, Finck A, Blair GJ, Tandon HLS. Plant nutrition for food security. A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin. 2006;**16**(368)

[45] Li C, Lei J, Zhao Y, Xu X, Li S. Effect of saline water irrigation on soil development and plant growth in the Taklimakan Desert Highway shelterbelt. Soil and Tillage Research. 2015;**146**:99-107

[46] Wassmann R, Jagadish SVK, Heuer S, Ismail A, Redona E, Serraj R, et al. Climate change affecting rice production: The physiological and agronomic basis for possible adaptation strategies. Advances in Agronomy. 2009;**101**:59-122

[47] Chapagain T, Yamaji E. The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. Paddy and Water Environment. 2010;**8**:81-90

[48] Das TK, Bhattacharyya R, Sudhishri S, Sharma AR, Saharawat YS, Bandyopadhyay KK, et al. Conservation agriculture in an irrigated cotton–wheat system of the western Indo-Gangetic Plains: Crop and water productivity and economic profitability. Field Crops Research. 2014;**158**:24-33

[49] Fischer RA. The effect of duration of the vegetative phase in irrigated semi-dwarf spring wheat on phenology, growth and potential yield across sowing dates at low latitude. Field Crops Research. 2016;**198**:188-199

[50] Gopal R, Jat RK, Malik RK, Kumar V, Alam MM, Jat ML, et al. Direct dry seeded rice production technology and weed management in rice based systems. Gates Open Research. 2019;**3**(207):207

[51] Gutiérrez J, Villa-Medina JF, Nieto-Garibay A, Porta-Gándara MÁ. Automated irrigation system using a wireless sensor network and GPRS module. IEEE Transactions on Instrumentation and Measurement. 2013;**63**(1):166-176

[52] Costa JM, Ortuño MF, Chaves MM. Deficit irrigation as a strategy to save water: Physiology and potential application to horticulture. Journal of Integrative Plant Biology. 2007;**49**(10):1421-1434

[53] Kajla M, Yadav VK, Chhokar RS, Sharma RK. Management practices to mitigate the impact of high temperature on wheat. Journal of Wheat Research. 2015;**7**(1):1-12

[54] Nagrare VS, Kranthi S, Biradar VK, Zade NN, Sangode V, Kakde G, et al. Widespread infestation of the exotic mealybug species, *Phenacoccus solenopsis* (Tinsley) (Hemiptera: Pseudococcidae), on cotton in India. Bulletin of Entomological Research. 2009;**99**(5):537-541

[55] Javed K, Jabbar A, Bhatt S, Mahmood K, Javed B. A comparative study of various controlling methods to monitor pink bollworm (*Pectinophora Gossypiella*) infestation on the yield of cotton: A case study of district Vehari, Pakistan. Big Data in Agriculture (BDA). 2020;**2**(1):29-31

[56] Hill DS. Pests of Crops in Warmer Climates and their Control. Springer Science & Business Media; 2008

[57] Conboy NJ, McDaniel T, George D, Ormerod A, Edwards M, Donohoe P, et al. Volatile organic compounds as insect repellents and plant elicitors: An integrated pest management (IPM) strategy for glasshouse whitefly (*Trialeurodes vaporariorum*). Journal of Chemical Ecology. 2020;**46**:1090-1104

[58] Mohan KS, Ravi KC, Suresh PJ, Sumerford D, Head GP. Field resistance to the *Bacillus thuringiensis* protein

Cry1Ac expressed in Bollgard® hybrid cotton in pink bollworm, *Pectinophora gossypiella* (Saunders), populations in India. Pest Management Science. 2016;**72**(4):738-746

[59] Dong HZ, Li WJ. Variability of endotoxin expression in Bt transgenic cotton. Journal of Agronomy and Crop Science. 2007;**193**(1):21-29

[60] Dent D, Binks RH. Insect Pest Management. Cabi; 2020

[61] Zafar MM, Zhang Y, Farooq MA, Ali A, Firdous H, Haseeb M, et al. Biochemical and associated agronomic traits in *Gossypium hirsutum* L. under high temperature stress. Agronomy. 2022;**12**(6):1310

[62] Brown JK, Khan Z. Breeding cotton for cotton leaf curl disease resistance. In: Cotton Breeding and Biotechnology. Boca Raton, Florida, United States: CRC Press; 2022. pp. 171-197

[63] Priya R, Ramesh D, Khosla E. Biodegradation of pesticides using density-based clustering on cotton crop affected by *Xanthomonas malvacearum*. Environment, Development and Sustainability. 2020;**22**:1353-1369

[64] Sattar T. A sociological analysis of constraining factors of development in agriculture sector of Pakistan. Journal of Economics and Sustainable Development. 2012;**3**(8):8-24

[65] Kaur S, Kaur R, Chauhan BS. Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. Crop Protection. 2018;**103**:65-72

[66] Heap I, Duke SO. Overview of glyphosate-resistant weeds worldwide. Pest Management Science. 2018;**74**(5):1040-1049

[67] Yuan D, Bassie L, Sabalza M, Miralpeix B, Dashevskaya S, Farre G, et al. The potential impact of plant biotechnology on the millennium development goals. Plant Cell Reports. 2011;**30**:249-265

[68] Iqbal N, Manalil S, Chauhan BS, Adkins SW. Investigation of alternate herbicides for effective weed management in glyphosate-tolerant cotton. Archives of Agronomy and Soil Science. 2019;**65**(13):1885-1899

[69] Zhu J, Wang J, DiTommaso A, Zhang C, Zheng G, Liang W, et al. Weed research status, challenges, and opportunities in China. Crop Protection. 2020;**134**:104449

[70] Rana SS, Rana MC. Principles and Practices of Weed Management. Palampur: Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya; 2016. p. 138

[71] Chauhan BS, Ahmed S, Awan TH, Jabran K, Manalil S. Integrated weed management approach to improve weed control efficiencies for sustainable rice production in dry-seeded systems. Crop Protection. 2015;**71**:19-24

[72] Duke SO, Gutterman Y. Flowering, seed development, and the influences during seed maturation on seed germination of annual weeds. In: Weed Physiology. Boca Raton, Florida, United States: CRC Press; 2018. pp. 1-25

[73] Bergtold JS, Ramsey S, Maddy L, Williams JR. A review of economic considerations for cover crops as a conservation practice. Renewable Agricultural Food System. 2019;**34**:62-76

[74] Lund-Thomsen P, Riisgaard L, Coe NM, Singh S, Ghori S. Bridging

Global Standard Requirements and Local Famer Needs: Implementing Parterns of the Better Cotton Initiative in Pakistan and India. Copenhagen Business School [wp]. CBDS Working Paper No. 1, 2018

[75] Lee JSH, Rist L, Obidzinski K, Ghazoul J, Koh LP. No farmer left behind in sustainable biofuel production. Biological Conservation. 2011;**144**:2512-2516

[76] Addis T, Kachi A, Wang J. A review of current state and future directions of cotton production in Ethiopia. Cogent Food & Agriculture. 2021;**7**:1880533

[77] Bitzer V, Glasbergen P. Business–NGO partnerships in global value chains: Part of the solution or part of the problem of sustainable change? Current Opinion in Environment Sustainability. 2015;**12**:35-40

[78] Hardin RG IV, Barnes EM, Delhom CD, Wanjura JD, Ward JK. Internet of things: Cotton harvesting and processing. Computers and Electronics in Agriculture. 2022;**202**:107294

[79] Martins SB, Vascouto V. Challenges to present fashion consuming society and market possibilities of organic cotton: A sustainable proposition. In: International Symposium on Sustainable Design, UFPR, Curitiba. Citeseer; 2007

[80] Allwood JM, Laursen SE, de Rodriguez CM, Bocken NM. Well dressed?: The present and future sustainability of clothing and textiles in the United Kingdom. Journal of the Home Economics Institute of Australia. 2015;**22**(1):42

[81] Amos CC, Rahman A, Gathenya JM, Friedler E, Karim F, Renzaho A. Roof-harvested rainwater use in household agriculture: Contributions to the sustainable development goals. Water. 2020;**12**(2):332

[82] Raynolds LT, Murray D, Heller A. Regulating sustainability in the coffee sector: A comparative analysis of third-party environmental and social certification initiatives. Agriculture and Human Values. 2007;**24**(2):147-163

[83] Bolwig S, Gibbon P, Jones S. The economics of smallholder organic contract farming in tropical Africa. World Development. 2009;**37**(6):1094-1104

[84] Vermeulen W, Uitenboogaart Y, Pesqueira LD, Metselaar J, Kok M. Roles of governments in multi-actor sustainable supply chain. Governance Systems and the Effectiveness of Their Interventions. An Exploratory Study. 2010

[85] Parikh TS, Patel N, Schwartzman Y. A survey of information systems reaching small producers in global agricultural value chains. In: 2007 International Conference on Information and Communication Technologies and Development. Piscataway, New Jersey, United States: IEEE; 2007. pp. 1-11

[86] Seuring S, Müller M. Core issues in sustainable supply chain management – A Delphi study. Business Strategy and the Environment. 2007;**2**(7):1-13

[87] Ahmad F, Perveen A, Mohammad N, Ali MA, Akhtar MN, Shahzad K, et al. Heat stress in cotton: Responses and adaptive mechanisms. In: Cotton Production and Uses: Agronomy, Crop Protection, and Postharvest Technologies. Springer Nature Singapore Pvt. Ltd; 2020. pp. 393-428

[88] Wang N, Qi H, Qiao W, Shi J, Xu Q, Zhou H, et al. Cotton (*Gossypium hirsutum* L.) genotypes with contrasting K+/Na+ ion homeostasis: Implications for salinity tolerance. Acta Physiologiae Plantarum. 2017;**39**(3):77

[89] Sharif I, Aleem S, Farooq J, Rizwan M, Younas A, Sarwar G, et al. Salinity stress in cotton: Effects, mechanism of tolerance and its management strategies. Physiology and Molecular Biology of Plants. 2019;**25**:807-820