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ASSESSING POTATO CULTIVATION TECHNIQUES IN PAKISTAN: AN ANALYSIS OF EXISTING METHODS AND IDENTIFIED GAPS

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Abstract *The potato is an important crop in vegetables. It is grown in sandy to clay-loamy soil in the winter season. Potassium and vitamin C are abundant in potatoes. Both governmental and private agriculture extension services actively educate farmers about suggested techniques for producing potatoes and offer guidance on how to implement these practices. This study aimed to investigate the discrepancy between accepted and advised potato production technology techniques. Pakistan's primary potato hub is Okara. Tehsil Okara was selected randomly from 3 tehsils (Okara, Depalpur, Renala Khurd) of district Okara. A random sampling was carried out for 120 Okara potato growers, the study's key data were gathered through a field survey. According to the survey, most farmers were aware of the suggested potato production technology and many had already embraced it. However, a sizable portion did not follow the advised guidelines. Therefore, to get a high yield of potatoes per acre, it is necessary to strengthen the efforts of extension services and implement more advanced advice. Extension activities must be adjusted to farmers' needs.*

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Introduction

Drought is a predominant environmental pressure Potato *(Solanum tuberosum)* is central in Pakistan's Agriculture Industry and is one of the most famous vegetables worldwide (Khalil et al., 2021; Majeed and Muhammad, 2018). Potatoes have incredible nutritional features, making them vital for the foremost non-cereal food groups and maintaining a well-balanced diet (Islam, 2024; Raigond et al., 2024). Potato is rich in carbohydrates, protein, and potassium with abundant vital vitamins, which boosts immunity and human health (Bhutto et al., 2024). Okara district remains the most productive district of Potatoes and potato crops hold a greater importance in Pakistan's economy (Rasool et al.; Riaz et al., 2024). The effect of increasing temperatures in the climate tremendously affects the tuber yield (Skrobacz et al., 2024). Okara's perfect climate and soil characteristics, such as deep, fertile, sandy to clay loamy soils with excellent water retention abilities, promote optimal potato growth (Sun et al., 2024). The fall season, that is, September to February, contributes about 70–75% of the potato production; the summer and spring seasons contribute 15-20% and 7–10% (Kim and Webber, 2024; Ntuli, 2024). Effective production methods have played an important role in improving potato yield and quality (Mishra et al., 2024). However, ideal practices can often be very far from what farmers do on the field (Drescher et al., 2024). There is frequently a notable gap between the suggested practices and the actions taken by farmers (Jafari et al., 2024; Priya and Singh, 2024) Organizations in the private and public sectors, such as those involved in producing fertilizer, seeds, and pesticides, play a vital role in spreading information about recommended practices (Alhassan et al., 2024; Dar et al., 2024).Various private sector organizations have hired field workers to enhance farming techniques and offer extension support (Pandey et al., 2024). This review article gave information on differences that exist between recommended and traditional used practices that significantly boost advancement in potato growing techniques.

Evolution of Potato Cultivation Practices

Potato industry in the Pakistan zone has changed remarkably concerning the economic needs of environmental issues of people and the better technological inputs (Bomers et al., 2024; Wang and Su, 2024). The advancement of technology in agriculture zone increased the productivity and enhanced yield of crops (Shah et al., 2024). The use of high-yielding seed varieties, irrigation facilities, and the latest techniques of fertilizers are common

examples (Yang et al., 2023). Modernization of potato farming in central locations such as Okara, the center for potato cultivation in Pakistan, has affected many methods of potato growing, including land preparation and harvesting (Farid, 2023; Mehta and Badegaonkar, 2023). Modern storage facilities and IPM systems recently improved post-harvest processing and storage, reduced losses, and facilitated obtaining market prices for farmers. Another factor that has supported the adopting of new technology and techniques by potato-producing farmers was the agricultural extension programs, where new technology and techniques were introduced to them by experts (Hamasalih and Layeeq, 2023).

Historical Trends in Potato Production in Pakistan

Potato crops were introduced in the mid-twentieth century, and its yield has importantly better with the application of modern growing techniques (Çalışkan et al., 2023). Potatoes were first grown on small farm fields in the okara district. After a considerable period, productivity and efficiency became much better with the incorporation of new modern techniques including resistant varieties against many diseases, and better soil management among others (Reddy, 2024; Zuza et al., 2024). In the 1980s, there was a massive growth in the area under potato cultivation, particularly in Punjab, which accounts for close to 90% of all potatoes in the state (Shah et al., 2023; Wani, 2023). Okara region has appeared as the top producer of potato due to its perfect soil and climate conditions (Ginting et al., 2024). Autumn, Summer, and Spring are the three major seasons of Potato Production (Bomers et al., 2024). In recent years the economic losses of Potato Production have been maximized due to fluctuations in output resulting from water deficiencies and climatic factors, making uninterrupted production difficult (Ierna, 2023; Obidiegwu et al., 2015)

Current Potato Production Technologies

Land Preparation Techniques

Soil preparation is very crucial in the increase of potatoes because it structures the soil, increases drainage, and makes nutrients available in the soil (Djaman et al., 2022; Johansen et al., 2015). Tractor-mounted plows and rotavators have successfully taken the place of the old manual method in areas such as Okara main growing region for potatoes in Pakistan (Mehta and Badegaonkar, 2023). It initiates with heavy plowing, harrowing, and leveling the surface of the field which will produce a fine tilth suitable for tuber production and root growth (Dua et al., 2018; Laxminarayana et al., 2016). The recommendations of a farmer for bed planting systems as a solution to combating waterlogging that can lead to diseases such as blight (Laxminarayana et al., 2016). The use of mechanical methods for land preparation leads to higher yields by enhancing aeration and controlling weeds, as well as saving time and labour (Ghorai, 2022). Most small-scale farmers in developing countries still use the traditional ways of farming. Such practices have resulted in less production compared to the utilization of modern machinery (Kansanga et al., 2019; Liao et al., 2022)

Sowing Methods and Timing

The success of the potato crop is largely dependent on the timing and technique of seeding (Liao et al., 2022). In Pakistan, the autumn (September–October) and spring (February–March) are the primary times for sowing potatoes (Ahmed et al., 2020; Naz et al., 2022). More than 70% of the overall potato production comes from the greatest crop, which is the autumn harvest (Dean, 2018; Stark et al., 2020). Ridge sowing and flat sowing are the two basic techniques used by farmers for sowing (Khan et al., 2015b; Tang et al., 2024). Ridge planting is the most used technique in the potato field because it lowers the chance of diseases through improved drainage and aeration, as well as planting seed potatoes on elevated beds (Thooyavathy et al., 2013). Ridge sowing gives higher tuber size and better crop yield. In this respect, flat sowing benefits especially in water-logged areas (Zhao et al., 2014). A higher plant depth of 8-12 cm and increased row spacing of 75 cm can increase tuber growth and facilitate mechanical harvesting (Dagne, 2015). The weather in rainfed regions is extremely unpredictable, which is a significant challenge when planting time occurs, also having an impact on the quality and yield of the crop (Liliane and Charles, 2020)

Seed Selection and Varieties

One of the major components of successful potato cultivation is the availability of high-quality seed tubers (Wasilewska-Nascimento et al., 2020). Pakistani farmers generally favour disease-free seed tubers since they have greater potential to produce better and higher crops (Almekinders et al., 2019; Khan et al., 2023). The best widely planted varieties in Pakistan are Desiree, Sante, Lady Rosetta, and Diamant and each is valued for different attributes like resistance to pests, higher yields, and tolerance to local climate conditions (Ahmad et al., 2021)**.** Seed companies in Pakistan produce seed locally or import seed from authorized ones in the Netherlands (Jafri et al., 2022; Schreinemachers et al., 2021). In recent years, Punjab Seed Corporation as well as other related organizations promoted the cultivation of high-yielding, disease-resistant cultivars (Rana et al., 2022). Most smallholder farmers tend to use low-quality or reprocessed seed tubers that may reduce productivity and predispose the crop to secondary diseases, such as late blight (Linguya, 2020; Rana et al., 2022). Most of the research centers in Pakistan, such as the National Agricultural Research Centre (NARC), focused on developing new, locally adapted varieties with higher resistance to pests and environmental stresses for improved seed quality (Babar et al., 2020; Ullah et al., 2020). Fungicide-treated seeds have emerged as one of the strategies for reducing disease risk during early development (Ayesha et al., 2021).

Irrigation Practices

Potato farming depends deeply on irrigation, especially in zones of Pakistan with inadequate water supplies (Majeed and Muhammad, 2018). Flood and furrow irrigation are frequently used for irrigation purposes, although they are ineffective and can often result in severe water loss (Guo and Li, 2024). Conventional techniques raise the danger of diseases like root rot and other fungal infections, which are harmful to potato crops and can result in waterlogging (Maciag et al., 2024). These conventional methods are very cheap and affordable; hence the farmers in the state of Punjab heavily depend on such practices as stated by different research conducted within the area (Anand and Kaur, 2024). Drip irrigation is one tool to enhance water-use efficiency, since water straight to the plant's root system (Alomran and Louki, 2024; Lakhiar et al., 2024). This method saves water and increases crop productivity; in fact, yields for potatoes were increased by 20% for farmers adopting drip irrigation compared to other conventional methods of irrigation (Kale et al., 2024). One of the main barriers that limit its wide-scale adoption is cost and availability (Panchalingam et al., 2024; Singh et al., 2024c). Government support and training programs would facilitate more farmers adopting these efficient forms of irrigation.

Fertilizer Application Methods

Fertilizer forms another key aspect of Pakistani potato cultivation. Potassium (potassium sulfate), Phosphorus (DAP), and nitrogen (urea) are the three most commonly used fertilizers (Tolessa, 2021; Wakeel and Magen, 2017). This crop requires high levels of these minerals for it to produce high yields efficaciously and effectively (Iqbal, 2019). Fertilizer is usually applied at a later stage during the crop growth cycle and in the soil preparation processes (Chojnacka et al., 2024). However, most farmers use fertilizers without proper testing of their soils hence nutrients are wasted (Srivastav et al., 2024). Over- and under-application can also end up harming the health of the soil and the yield of crops in the long term (Li et al., 2024). Recent studies reveal that the use of applied methods for maintain the yields for potatoes could double to 15-20% higher than traditional methods (Ouda and Zohry, 2024). Organic and biofertilizer usage is becoming more popular to encourage sustainable farming methods and reduce their dependence on chemicals (M. R. Khan et al., 2022). Compost and farmyard manure are the organic fertilizers, which enhance the soil fertility and main soil structure (Rostaei et al., 2024; Zhou et al., 2024a). Organic fertilizers have some benefits, but they are not usually used due to their shortage in the countryside and lack of knowledge about them. More work would be needed to support balanced fertilizer use and sustainable practices based on soil testing to increase productivity.

Plant Protection Measures

Potatoes are highly prone to various pests and diseases, plant protection is one of the major issues in potato production (Ahmadu et al., 2021). Late blight and early blight along with potato virus Y are some of the major viral diseases present in potatoes (Kreuze et al., 2020; Lin et al., 2014). Farmers based in Pakistan generally rely on chemical pesticides and fungicides to protect their crops from such diseases (Khan et al., 2015a). However, excessive use of chemical pesticides not only increases the cost of production but also hazards the environment as a whole (Carvalho, 2017; Özkara et al., 2016). Farmers use fungicides and insecticides as a precaution, disregarding crop needs and pest levels (Afari-Sefa et al., 2015). An emerging alternative to chemical-intensive farming is integrated pest management or IPM (Sharma et al., 2016). Biological control agents, resistant potato varieties, and targeted pesticide application based on pest scouting and monitoring are just a few of the approaches that are incorporated into integrated pest management (IPM)(Gao et al., 2024). Pakistan has a low acceptance rate of IPM methods due to a lack of knowledge, training, and technological access (Khan et al., 2021). Mechanical weeding is used with pesticides to manage weed populations in potato fields. Encouraging IPM could increase yields, reduce costs, and lessen environmental impact, but requires significant support services and farmer education (El-Metwally and El-Wakeel, 2019; Kebede et al., 2016).

Harvesting and Storage Practices

Potato quality and shelf life are determined by harvesting and storing methods, with potatoes typically harvested in Pakistan 90-120 days after planting (Abbasi, 2012). Hand harvesting is hard for small farmers. Mistakes like rough handling or early picking can lower quality and capacity (Stark et al., 2020). While large farms use mechanical harvesting, small-scale farmers often find the equipment expensive (Mujawamariya and Kalema, 2017). Potato storage is a challenge for many farmers in conventional farming systems due to inadequate facilities, leading to significant post-harvest losses (Degebasa, 2020; Kuyu et al., 2019). Modern cold storage facilities have reduced losses by 40% through humidity and temperature control (Amirali, 2017; Makule et al., 2022). Small farmers struggle to afford cold storage. Accessible and affordable cold storage could make potato cultivation more profitable in areas like Okara Market power: Traders, farmers, and the politics of accumulation in Pakistani Punjab (Rashid, 2023). The Integrated Pest Management system utilizes Biological, Cultural, Mechanical, and Chemical techniques to ensure sustainable control of potato pests are described in Fig 1.

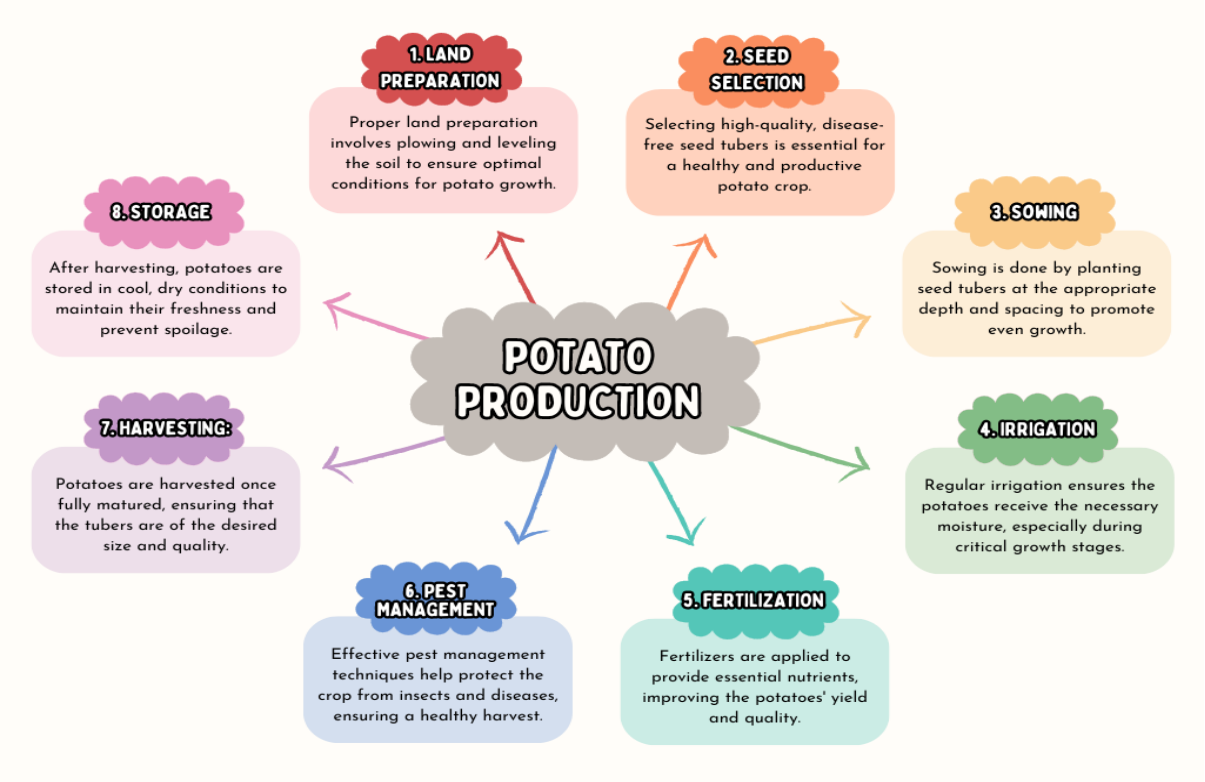

Fig 1. Flowchart illustrating the stages of potato production from land preparation to storage, highlighting the interconnected processes for efficient crop management

Advances in potato production

Innovations in Seed Technology

High potato yields rely heavily on seed quality, with developments in seed science leading to disease-resistant and high-yielding potato cultivars like "Sante," "Diamant," and "Lady Rosetta" being introduced in Pakistan (Khan et al., 2023). Tissue culture technology allows for mass production of virus-free seed potatoes, boosting yields by up to 25% compared to conventional seeds (Muthoni and Kabira, 2014; Umaro, 2022). Seed priming techniques are also being utilized to improve germination and early growth (Singh et al., 2015). These advancements are advantageous for farmers looking to maintain healthy crops and increase overall crop performance, particularly in challenging conditions (Fischer and Connor, 2018).

Modern Irrigation and Fertilization Techniques:

In potato production, the integration of modern fertilization and irrigation techniques has resulted in higher yields and efficient use of resources (Djaman et al., 2021). The application of Precision farming technologies such as drill and sprinkler irrigation plays a critical role in enhancing the productivity and sustainability of agriculture by optimizing water usage which helps plants take water for the root zone (Lakhiar et al., 2024; Neupane and Guo, 2019). Drip irrigation, in particular, minimizes leaf wetness, which is a common issue in traditional flood irrigation systems, and reduces water waste (Asres, 2023; Sidhu et al., 2021). The farmers adopting drip irrigation yield higher and utilize water more judiciously as water is becoming scarce in Pakistan (Iqbal and Iqbal, 2015). Fertilization is also a new development with fertigation, and therefore, quite an accurate delivery of nutrients can be achieved by fertilizing through the irrigation system as compared with other previous fertilizations (Chojnacka et al., 2020; Incrocci et al., 2017). Fertilizer runoff is reduced, and the needed amount of plant nutrients is applied to the plant at the right growing stage (Davidson and Gu, 2012; Li et al., 2009). Long-term sustainability in potato cultivation is encouraged while enhancing soil health and nutrient use efficiency with the adoption of slow-release and biofertilizers as well (Ierna and Distefano, 2024; Srinivasarao, 2021).

Integrated Pest Management (IPM)

Integrated Pest Management in potato farming is a step towards reducing chemical pesticides considerably and promoting eco-friendly ones (Ierna and Distefano, 2024). In Pakistani IPM programs, the use of biological controls, resistant potato cultivars, and chemically targeted treatments, guided by pest monitoring and thresholds, is implemented (Naqqash, 2023; Razaq et al., 2019). Predatory insects and fungi have greatly diminished the use of chemical treatments to manage pests like aphids and nematodes (Skinner et al., 2014). As shown in Fig 2, the IPM system combines the application of Biological, Cultural, Mechanical, and Chemical Control Methods for the sustainable management of potato pests. During IPM, pheromone traps and biopesticides are also applied (Jhala et al., 2020). These methods are safer for both human beings and the environment. The

resource constraints and knowledge inadequacy among smallholding farmers limit the use of IPM strategies (Ochago, 2018). In this regard, extension services and training programs are important for the increased adoption of IPM practices that have yield-increasing potential as well as decreasing environmental impacts of potato farming(Abebe et al., 2013).

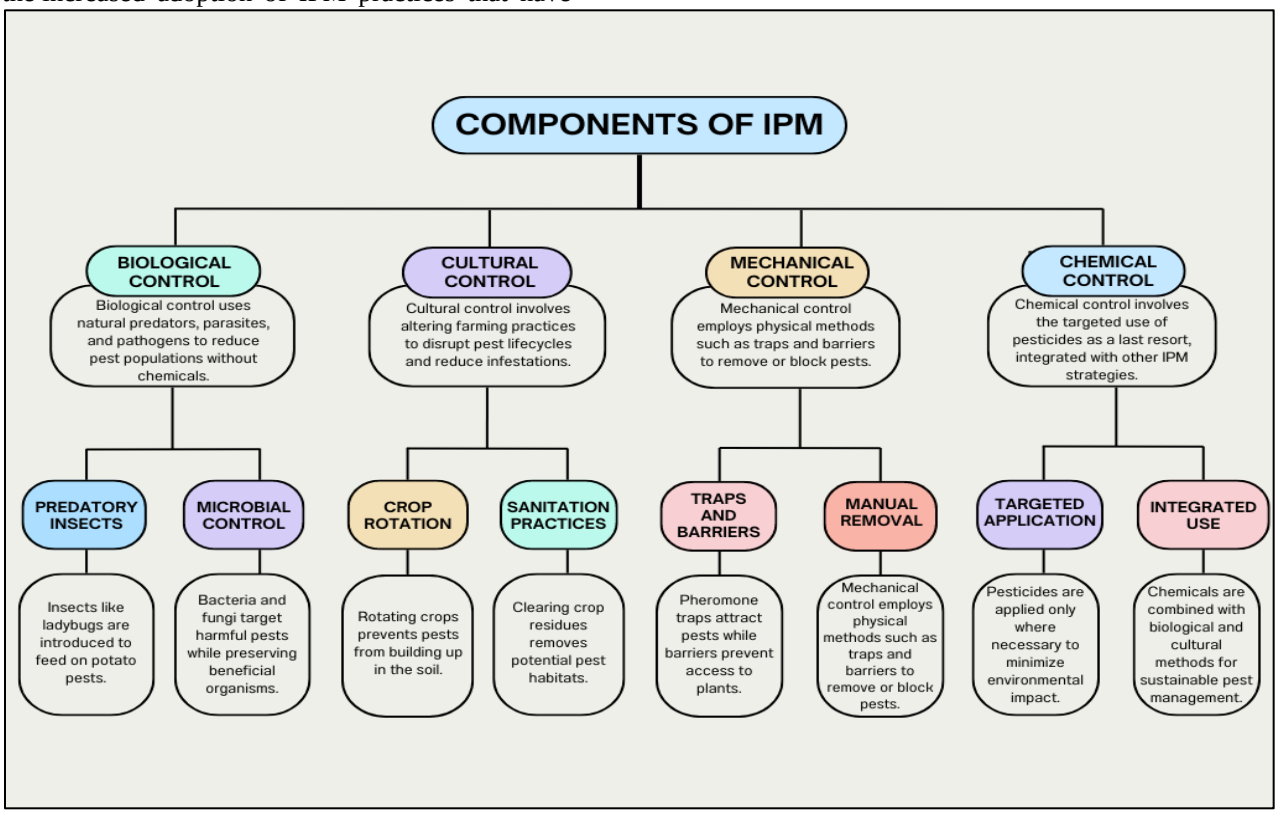

Figure 2. Integrated Pest Management (IPM) system showing the grouping of Biological, Cultural, Mechanical, and Chemical Control Methods for Sustainable Pest Management in Potato Production.

Soil and Water Conservation Practices

Soil Productivity and water scarcity are some of the major constraints that require adoption of eco-friendly soil and water conservation practices. Potato industry can adopt crop management practices that are promising, such as mulching and cover cropping, to increase soil organic matter, reduce soil erosion, and maintain the soil moist (Alyokhin et al., 2020; Ngosong et al., 2019). Preserving the water in the arid regions of Pakistan is highly important; using organic material like straw or plastic mulch helps to conserve soil moisture (El-Beltagi et al., 2022; Javed et al., 2019). Traditional techniques like rainwater harvesting and moisture checking are skills that build irrigation techniques and crop productivity in drought-prone regions (Abdullah and Rahman, 2015; Yazar and Ali, 2016). This improves conservation tillage since it reduces erosion and conserves the health of soils; thus, it promotes sustainable production of potatoes in Pakistan through maximum resource utilization (Arshad et al., 2023).

Adoption of Recommended Practices

Factors Influencing Adoption Rates

Social and ecological factors are very significant in the production methods of potatoes around different areas of Pakistan. The adoption of the latest recommended practices is influenced by the farm size influenced by farm size, education of farmers, financial resources, and awareness of new agricultural technologies (Akudugu et al., 2012; Quddus, 2012). The most recent technology is likely to be adopted by better-educated farmers due to the convenience offered by the extension services department (Ahmed and Adisa, 2017). Most large-scale farmers are more likely to opt for costly technologies as compared to smallholder farmers (Derpsch et al., 2016). New agricultural technologies in the village areas discourage adopting new technologies due to a lack of modern machinery. Insecure land tenure discourages long-term investment (Fofanah, 2020; Gulati et al., 2021). These include education, financial incentives, and access to technology to improve the best agriculture practices being practiced in Pakistan.

Case Studies and Regional Variations

Okara is one of the strongest provinces in Pakistan with good agricultural infrastructures and high-class potato farming skill that maximizes production as well as utilizing the productive resources (Aslam, 2016). It is slow adopting areas mainly KPK and Baluchistan due to the less strong networks of agriculture extension services, inaccessible service by extension, as well as harsh climate of those places

(Kamal et al., 2022; Saddique et al., 2022). Regional disparities affect potato technology adoption in the country of Pakistan (Majeed and Muhammad, 2018). A study in Punjab revealed that farmers in Faisalabad and Sahiwal with better access to extension services were more likely to adopt Pest Management and Fertilization Practices (Muddassir and Alotaibi, 2023). The use of Precision Agriculture Technologies is, however restricted by the cost and specialization (Riaz et al., 2024; Tey and Brindal, 2012). Thus, customized interventions are required to bridge regional disparities and facilitate diversified access to agricultural technologies (Marion et al., 2024).

Role of Agricultural Extension Services

The gap that exists between research-based recommendations and the practical implementation thereof by farmers is filled by the Agricultural Extension Workers (Bello Cartagena, 2019; Lemma et al., 2012). Public and Private Agricultural extension workers provide information of latest production technologies of potato growing in Pakistan(Sher et al., 2016). These officers offer information on seed selection, soil preparation, irrigation, and pest control to potato farmers during field visits, workshops, or demonstrations by the extension officers (Mudege et al., 2016; Shahzad et al., 2018). Still, the services offered by this agency may not be effective because of a variety of constraints that include poor accessibility of remote agricultural areas and lack of a skilled labor force (Poulton et al., 2010). Increasingly, the private sector business has assumed the role of extension services particularly on seed sales, fertilizers, and pesticides. This calls for public extension services and research-oriented guidance for farmers in order to advance sustainable Potato farming in Pakistan (Jalango et al., 2024).

Challenges and Gaps

Discrepancies Between Recommended and Actual Practices

One of the biggest drawbacks in Pakistani potato production is the farming practices gap between recommended and farmers' practices (Riaz et al., 2024). Most of the farmers are using traditional systems instead of new technologies, which results in lesser production (Devilliers et al., 2024; Misra and Ghosh, 2024). However, due to a lack of awareness and financial limitations, the promotion of improved irrigation and seed varieties, traditional methods are still prevalent in the village zone (Carroll II, 2024; Mpala and Simatele, 2024). Similarly, even though mechanized planting and harvesting techniques can significantly increase yield, most small-scale farmers still rely on labour-intensive manual techniques since technology is expensive (Randy et al., 2024; Sriram et al., 2024). Chemical pesticides or fertilizers are frequently used against advised guidelines, excessively or at the wrong periods, which lowers crop quality and harms the environment (Gaytancıoğlu and Yılmaz, 2024; Kumar and Reddy, 2024). Better education and more easily accessible resources for farmers are vital, as seen by the disparity between the adoption of advanced agricultural practices and conventional ways (Kumar and Reddy, 2024). The difference between the traditional and modern methods of potato production is illustrated with the help of Table 1.

Table 1. Traditional vs. Modern Potato Production Techniques

Practices	Traditional Method	Modern Method
Land Preparation	Manual plowing with oxen or basic tools	Mechanized tillage using tractors and rotavators
Seed Selection	Local, saved seeds from previous harvests	Certified, disease-free seeds from seed banks
Irrigation Methods	Flood irrigation, which wastes water	Drip or sprinkler irrigation for water efficiency
Fertilization Practices	Organic fertilizers like manure	Balanced chemical fertilizers and organic blends
Pest and Disease Control	Sole reliance on chemical pesticides	Integrated Pest Management (IPM) combines biological, cultural, and chemical methods.
Harvesting	Manual labor using hand tools	Mechanized harvesters for efficiency and speed

The table 1 highlights the variations in land preparation, seed selection, irrigation, fertilization, and pest control between conventional and modern potato farming methods. Integrated Pest Management (IPM), drip irrigation, certified seeds, and automated tillage are examples of modern techniques that are more sustainable and efficient than labour and resource-intensive conventional techniques (Raj et al., 2024). The comparison demonstrates how implementing modern farming techniques can enhance output and better manage resources. Table 02: Regional Challenges and Gaps in Adopting Modern Potato Production Technologies.

Table 2. Regional Challenges and Gaps in Adopting Modern Potato Production Technologies

Region	Challenge	Suggested Solution
Okara	High water use in irrigation	Promote drip irrigation to conserve water
Depalpur	Lack of access to certified seed	Implement government seed subsidy programs

Renala Khurd	Pest resistance	Adopt Integrated Pest Management (IPM) strategies

The table 2 highlights the specific problems in potato production for each area and the suggested solutions for them. Such methods are drip irrigation, certified seed programs, and IPM techniques that promote efficient and environmentally friendly farming practices.

Economic, Environmental, and Social Barriers

One of the main encounters in employing optional potato production technology is the cost factor (Samuel et al., 2024). Majorities of Pakistani potato farmers are small farmers, who cannot afford high-costing equipment, drip irrigation, and high-quality seeds (Waheed et al.). Such high input costs and high potato market prices discourage farmers from adopting new technologies that may increase their yields and profits (Chikhawo et al., 2024). In addition, since they lack tenure security associated with land ownership, tenants or farmers who rent their lands might be less likely to invest in long-term improvements, including soil conservation management practices (Hadera et al., 2024).

Environmental issues also cause gaps in potato output. In many areas, poor soil quality and limited water availability make it difficult to increase production (Geling, 2024; Ravensbergen et al., 2024). The adoption of sustainable agricultural techniques has been further hampered by the overuse of chemical fertilizers and pesticides, diminishing soil health, and water resource contamination as a result of a lack of knowledge about integrated pest management (IPM) (Rahman et al., 2024; Singh et al., 2024a). These challenges are compounded by social limitations, such as cultural conservatism and a lack of extension services (Limpamont et al., 2024). Moreover, many farmers are still relying on inherited knowledge that cannot include modern techniques suited to the needs of the market and environment today (Ihuah, 2024).

Impact of Climate Change on Potato Production

The potato crop in Pakistan is more vulnerable to climate change changes, mainly the shifting pattern of weather in Pakistan with increasing temperatures and erratic rainfall (Khan and Hussain, 2024; Saleem et al., 2024). They are very sensitive to temperatures, and above-average temperatures significantly affect the formation of tubers and their yield (Ghag et al., 2024). Potatoes grow well in cooler temperatures, but rising temperatures in the major producing regions of Punjab are shortening growing seasons and harvests (Naz et al., 2024b). Droughts and erratic monsoons worsen water shortages (Singh et al., 2024b).

In addition, an increased prevalence of diseases and pests resulting from climate change forces farmers to rely more on chemical pesticides that eventually may cause degradation of the environment and higher production costs (Khatri et al., 2024; Shafiq et al., 2024). Climatic change fluctuations widen already existing differences between recommended and actual potato production practices (Dushyant et al., 2024). The difference between the Environmental Impact Comparison of Traditional vs Modern Potato Farming Practices is described with the help of Table 3.

Table 3, Environmental Impact Comparison of Traditional vs Modern Potato Farming Practices

Impact Factor	Traditional Practices	Modern Practices
Water Use	High (Flood irrigation)	Reduced (Drip irrigation)
Soil Health	Declining (Over-tillage, soil erosion)	Improved (Crop rotation, reduced tillage)
Chemical Use	High (Overuse of fertilizers/pesticides)	Balanced (IPM techniques, precise application)
Carbon Footprint	High (Use of heavy machinery, inefficient practices)	Low (Sustainable practices, renewable energy)

The table 3 highlights developments in water conservation, soil health, chemical use, and carbon footprint, contrasting the environmental effects of old and modern potato farming methods. Modern methods to traditional ones, drip irrigation, crop rotation, and Integrated Pest Management (IPM) encourage environmentally friendly and sustainable potato production (Zhou et al., 2024b). SWOT Analysis of Potato Production in Pakistan, highlighting strengths (e.g., suitable climate, high demand), weaknesses (e.g., reliance on traditional methods), opportunities (e.g., technology adoption, export potential), and threats (e.g., climate change, water scarcity are described in table 4.

Figure 3. SWOT Analysis of Potato Production in Pakistan, highlighting strengths (e.g., suitable climate, high demand), weaknesses (e.g., reliance on traditional methods), opportunities (e.g., technology adoption, export potential), and threats (e.g., climate change, water scarcity).

Policy and extension services

Role of Public and Private Sector in Potato Production

In Pakistan, both the public and private sectors are equally crucial for the progress and development of technologies related to potato production (Khurshid et al., 2024; Rashid, 2024). Farmers must have access to information on better agricultural practices, such as pest control, irrigation methods, and seed selection, from the public sector, mostly through agricultural extension programs (Bhat et al., 2024; Sahu et al., 2024). Public Sector participation is restricted due to a lack of finance, poor infrastructure, and limited extension, mostly in rural areas (Kumar, 2024; Navarro-Valverde et al., 2024). The Private sector participation in potato cultivation has increased dramatically through agrochemicals, fertilizers, and seeds (Clement et al., 2024). Agricultural Companies give consultation extension services to boost the utilization of the latest methods and high productivity (Ataei et al., 2024; Raj, 2024).

Effectiveness of Extension Programs

Pakistan has provided similar results in terms of agricultural extension work to support potato production technologies (Raihan et al., 2024). Public extension services in the country are heavily constrained by factors such as less experienced institutions, outdated information, and unavailability for smallholder farmers in more remote parts of the country (Manzeke-Kangara et al., 2024; Sahu et al., 2024). This has resulted in many farmers not adopting new technologies or even being unaware of the new technologies (Steele et al., 2024). The availability of new technologies is limited, making small-scale farmers rely on the traditional practices that disallow them from adopting unaccustomed agricultural practices that have a resultant effect on the performance of their farm (Jadhav et al., 2024; Pandey et al., 2024). Some areas were better than others: there are places where successful sales networks have businesses. Businesses that promote their products are actively placed and marketed (Pandey et al., 2024; Tiwari et al., 2024). Such services, however focus much more on the adoptions of certain commercial things that are likely not doing as much for the broader issues affecting potato farmers, such as controlling water resources, and keeping soils healthy; (Potter et al, 2024; Schattman et al,2024). Greater public and private body interaction will ensure extension services are efficient because they provide integrated information for farmers that enhances both the productivity and sustainability of the farm outputs (Francis et al., 2024; Pandey et al., 2024).

Recommendations for Policy Improvement

Policy recommendations that would increase funding for public sector extension activities in Pakistan would increase potato production by hiring more officers and enhancing infrastructure in these remote areas (HAMEED et al., 2024; Khan et al., 2024). It is very crucial to get a mix of commercial and research-

based advice through enhanced collaboration between the public and the private sectors (Rossoni et al., 2024).Integrated pest management (IPM) and water conservation strategies should be encouraged by policy frameworks (Han et al., 2024; Yarahmadi and Rajabpour, 2024). Financial support or subsidies may also motivate smallholder farmers to adopt climate-friendly technologies and overcome financial barriers to investment in high technological means (Mao et al., 2024; Pedersen et al., 2024). The policymakers should als

o promote research on regionally adapted potato varieties resistant to climate change (Chege et al., 2024; Saleem et al., 2024).

Emerging Technologies and Practices

Future factors impacting Pakistan's potato production may include cutting-edge technologies and unique methods that enhance sustainability along with efficiency (Akhtar et al., 2024). Precision farming technologies, soil moisture sensors, GPS-guided planting and harvesting equipment, and drones are equally necessary for crop health monitoring (Lakhiar et al., 2024; Shah et al., 2024). Biotechnology provides an appealing prospect for future research, the development of genetically modified potato varieties for increased resistance to stresses such as drought and heat stress (Lakhiar et al., 2024; Mandal et al., 2024). Tissue culture, as quality seed production, mitigates the problem of certified seeds in the potato industry of Pakistan (Muthoni and Shimelis, 2023; Naz et al., 2024a). Organic farming practices such as bio-fertilizers and pest management are gaining increasing attention for sustainable practices (Akanmu et al., 2023).

Research Needs and Opportunities

Improved potato production faces a research gap, particularly in the development of climate-resistant varieties to cope with the shifting conditions in Pakistan (Ameen et al., 2023; Waris et al., 2023). Selection of cultivars appropriate for different agroecological zones can help stabilize yields as temperatures rise and uneven rainfall is observed due to climate change (Grigorieva et al., 2023; Pixley et al., 2023). Potato crops are regularly injured by common challenges like nutrient depletion and poor soil (Sadawarti et al., 2023). In addition, an investigation focusing on the impacts of different production technologies on smallholder farmers' social and economic conditions could provide valuable insights into promoting the wider adoption of improved methods (Bontsa et al., 2023). There is a need to educate the farmers at the district level and collaborate with government extension workers, research institutions, and commercial organizations to ensure practical innovations in the potato fields (Kumar et al., 2024; Van Dijk, 2023).

Potential for Sustainable Potato Production

There is a great concern for sustainability in agricultural practices for Potato production in Pakistan (Waheed et al., 2023). The farmers, in their practicality, employed the sustainability approach through crop rotation, organic farming, and using renewable energy resources on agricultural land (Akanmu et al., 2023; Selvan et al., 2023). Management practices based on conservation agriculture use techniques such as cover crops, minimal tillage, etc (Angon et al., 2023; Jasrotia et al., 2023). This increases the fertility of the soil while saving water and preventing soil erosion effectively (Ndegwa et al., 2023). The techniques of Integrated Pest Management can reduce reliance on chemical pesticides and can decrease the pollution level in the atmosphere, thus enhancing environmental well-being (AbuQamar et al., 2024; Awasthi et al., 2023). In water-scarce regions, drip irrigation systems and harvesting rainwater should be implemented together to ensure sustainable practice in the long term (Gürsu, 2024; Talafha et al.). Encouraging farmers in Pakistan to implement these methods through legal incentives and educational programs can lead to an eco-friendly future for potato production(Mehta and Badegaonkar, 2023).

Conclusion

Although Potato Production is an important industry in Pakistan not only from economic and nutritional points of view, the sector may be plagued by serious problems. Major issues revolve around the disparity between recommended practices and actual farm-level management practices mainly followed by small-scale farmers. They still use old seed conservation methods and traditional methods of irrigation. These typically reduce yields, and make the crops more susceptible to disease. Fertilizers are applied in ways that do not improve soil health, and chemical pesticides create particular environmental hazards. Inadequate storage facilities and poor harvesting enhance the post-harvest losses. To address this issue, the Agricultural Extension Department needs to work on the financial constraints that hinder technology adoption. Climate change is also a major threat for potato cultivars and sustainable farming practices are required to enhance maximum output. Future efforts must be designed on innovative technologies, productive research, and policies helpful for productivity and sustainability. Pakistan can boost its potato industry by fostering a supportive environment, contributing to economic growth and food security.

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Declarations

Declaration of Interest Statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work.

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Author's contributions

MFI and NF conducted the field trials and planned the experiment. MZH analyzed the data. FA and NF assisted with data collection. All authors proofread the manuscript. All authors have read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable

Consent for Publication

Not applicable