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Agricultural Dynamics in the Kashmir Valley: Adapting Rabi Crop Cultivation to Temperate Challenges

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Abstract

The Kashmir Valley's temperate climate presents unique challenges and opportunities for Rabi crop cultivation. This study investigates how local farmers are adapting to the region's extended cold spells and unpredictable weather by adopting cold-resistant crop varieties and optimized cultivation practices. Key Rabi crops, including wheat, mustard, oats, peas, and saffron, are analyzed for their resilience to frost and their contributions to food security and economic stability in the valley. Improved mustard and oat varieties exhibit high resistance to freezing temperatures, while saffron and peas demonstrate significant economic and nutritional importance. These adaptive strategies underscore the Valley's agricultural resilience, ensuring sustainable yields under harsh conditions. Agriculture in the Kashmir Valley encounters severe winter challenges, including prolonged frost, sub-zero temperatures, and heavy snowfall, all of which disrupt crop and livestock productivity. These harsh conditions delay germination, stifle plant growth, and restrict nutrient uptake, while extended snow cover limits sunlight exposure, essential for early crop development. Cold temperatures also strain livestock management, raising feed demands and increasing health issues. To combat these adverse effects, local agricultural initiatives promote cold-resistant and frost-tolerant crop varieties such as Sabzar and SFO-1 oats, and mustard varieties like SS-II and COS 101. These improved varieties are bred for resilience, faster growth cycles, and higher yields, enabling more reliable agricultural returns even in extreme winter conditions. By adopting these cold-adaptive varieties, farmers can enhance productivity, economic stability, and the sustainability of agricultural practices within the Valley's challenging environment.

***Key words*:** Rabi crops, Temperate challenges, Crop varieties, Cold-adaptive varieties, Saffron, Oilseeds

The Kashmir Valley, known for its stunning landscapes and temperate climate, faces unique challenges when it comes to agricultural activities [1]. As the autumn leaves fall and the air turns crisp, farmers across the region begin the vital task of sowing Rabi crops, which are grown during the winter season and harvested in spring. Despite the valley's natural beauty, cultivating crops in this region is far from easy, particularly due to the harsh climatic conditions and prolonged chilling periods that the region experiences [2-3]. However, through perseverance and the adoption of improved crop varieties, the farmers of Kashmir continue to sow the seeds of prosperity, ensuring both food security and economic returns [4-5].

The Kashmir Valley, situated in the northwestern tip of Jammu and Kashmir, India, spans an elliptical, bowl-like area covering 15,948 square kilometers between latitudes 32°22′–34°43′ N and longitudes 73°52′–75°42′ E, at an elevation of approximately 1,577 meters above sea level. Enclosed by the Himalayan ranges, the valley forms a semi-closed ecosystem that is drained by the Jhelum River, a significant tributary of the Indus. The temperate climate here is ideal for diverse horticultural and agricultural crops, supported by an annual precipitation pattern with 60% of the rainfall and snowfall concentrated in December and January. Temperatures vary notably with altitude, creating distinct meso and microclimatic conditions across the valley that influence crop diversity and ecosystem characteristics [6].

Agriculture is the cornerstone of livelihoods in the Kashmir Valley, with most residents depending on it for sustenance and income. Given the region's environmental fragility and high susceptibility to climate change, especially in mountainous zones, any agricultural shifts can profoundly impact local livelihood patterns. Rice serves as the staple crop, while maize, apples, and pears also form essential parts of the agricultural landscape [7].

The Rabi season in Kashmir typically spans from October to December, aligning with the onset of cooler autumn and early winter months. During this period, winter crops are sown, taking advantage of the valley's temperate climate, which supports crops requiring cooler conditions for optimal growth. The season is critical for agriculture in Kashmir, as it enables the cultivation of a variety of food and cash crops that thrive in low temperatures and meet local food demands [8]. Key Rabi crops include wheat, mustard, oats, and barley, each adapted to the region's climate and soil types. Wheat, a staple food grain, benefits from the mild winter and is widely cultivated across the valley. Mustard is another significant crop, especially with the adoption of cold-tolerant varieties, offering farmers a source of oilseed even in frosty conditions. Similarly, oats are grown as

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both a grain and fodder crop, particularly cold-tolerant varieties like Sabzar and SFO-1, which withstand freezing temperatures and snow cover, thus ensuring adequate winter fodder for livestock [9]. The agricultural landscape of the Kashmir Valley, with its unique temperate climate, faces numerous challenges, particularly during the Rabi season. Despite adverse conditions, farmers in this region have adopted a range of resilient practices and crop varieties to mitigate the impacts of chilling temperatures, frost, and limited water resources. Through a targeted selection of crops and varieties adapted to cold weather—such as mustard, oats, and peas—alongside timely agricultural practices, they manage to optimize productivity, ensuring both food security and economic stability.

The valley's unique climatic conditions during the Rabi season contribute to steady yields, as the cool weather reduces pest pressure and slows disease progression. The moisture from winter precipitation in the form of rain and snow further aids crop establishment and growth, supporting the valley's agricultural productivity [10.

Innovative use of improved crop varieties like cold-tolerant oats (Sabzar and SFO-1), resilient mustard types (SS-II and COS 101), and frost-resistant pea strains demonstrates the adaptability and resourcefulness of Kashmir's farming communities. The integration of these high-yielding, stress-tolerant cultivars is pivotal to overcoming the climatic constraints of the region, which historically hinder agricultural productivity during the winter season. Additionally, the application of key nutrients, such as sulphur for oilseeds, further amplifies yield and quality, helping farmers achieve substantial economic gains and sustainable agriculture [11]. The ongoing focus on modernizing agriculture in Kashmir, through government support and farmer-driven innovation, signifies a promising future for the region. These adaptive strategies not only strengthen the resilience of the agricultural sector but also support the cultural and economic fabric of Kashmir. As climate uncertainties continue, fostering these practices will remain crucial in maintaining the valley's agricultural heritage while securing the livelihoods of its people.

Key aspects of rabi season in Kashmir

Sowing period: Crops are usually sown from October to December. The sowing process begins right after the Kharif crops (like paddy and maize) are harvested.

Climatic conditions

Cool temperatures: Kashmir experiences chilly winters, and many Rabi crops benefit from the cold and frost. However, excessive snowfall or prolonged cold spells can sometimes delay sowing or harm early-stage crops.

Irrigation dependence: Unlike Kharif crops that rely heavily on monsoons, Rabi crops depend more on irrigation from rivers, canals, and tube wells since precipitation is relatively lower during this time.

Major rabi crops

Oilseeds: Mustard is widely cultivated.

Fodder: Crops like Oats are also grown during this season.

Vegetables: Various winter vegetables, such as Peas, Saag (Khanyari and G. M. Dari), spinach, garlic etc. are grown extensively.

Saffron: Though cultivated in autumn, saffron is harvested during the Rabi season, particularly in districts like Pulwama (Pampore). Pampore, located in the Pulwama district of Kashmir, holds the distinction of being the saffron capital of the region and is globally recognized for its high-quality Kashmiri saffron (*Crocus sativus* Kashmirianus) [12]. This unique spice, famed for its deep red color, potent aroma, and rich flavor, is harvested here annually during a short window from late October to mid-November. During this period, saffron flowers bloom on the cold, well-drained soils of Pampore, producing vibrant crimson stigmas that are carefully handpicked, dried, and processed to produce saffron threads [13].

Out of Kashmir's total 5,707 hectares dedicated to saffron cultivation, Pampore alone accounts for over 90 percent [14]. This concentration is due to Pampore's unique climate and soil composition, which are particularly conducive to saffron cultivation. The sandy, loamy soil of the area, combined with the cool, dry autumn climate, provides ideal conditions for saffron crocus growth. These factors contribute to the high-quality stigmas that distinguish Kashmiri saffron from other types grown globally, making it among the most prized varieties in the world [15].

The cultivation of saffron in Pampore is not only economically significant but also deeply embedded in the local culture. Saffron farming supports thousands of families in Pampore and surrounding villages, with the spice fetching premium prices due to its labor-intensive harvest process and exceptional quality. The importance of saffron to the region has also led to government initiatives aimed at supporting and modernizing saffron cultivation, with schemes designed to improve irrigation, processing, and market access for local farmers [16].

Harvesting

The harvesting of Rabi crops begins in March-May, depending on the crop and local conditions. By this time, temperatures gradually rise, signaling the end of winter and providing favorable conditions for crop maturity.

Challenges

Frost and snowfall: Extreme cold and heavy snowfall can damage tender plants or delay sowing.

Limited irrigation resources: Due to lower precipitation in winter, water management becomes critical.

The Rabi season in Kashmir provides a critical window for growing food crops that support the region's agrarian economy and ensure food security during the winter months.

Sowing rabi crops in temperate conditions

The temperate climate of the Kashmir Valley presents both opportunities and challenges for Rabi farming. Crops like oilseeds (mustard), oats (fodder), peas, and garlic are commonly sown during this season. However, the valley's cold winters and frost conditions demand precise timing and careful crop selection to ensure successful growth and productivity [17-18].

Mustard (Oilseeds)

Mustard (*Brassica spp.*), a significant oilseed crop in Kashmir, is usually sown in Mid-October or Late October. This crop thrives in the valley's cold winters, but its growth is often hampered by frost and cold waves that persist throughout the winter months. To mitigate the challenges of frost and chilling injuries during the Rabi season, farmers in Kashmir are adopting improved mustard varieties such as SS-II and COS 101 [19]. These varieties offer greater resistance to cold stress, helping ensure better crop survival, improved yields, and higher economic returns. This shift to more resilient mustard varieties is part of the farmers' strategy to adapt to the region's harsh

winter conditions while maintaining agricultural productivity. The prolonged cold in the valley means that sowing must be done with precision to avoid crop damage from early frosts. Additionally, mustard plants benefit from cold weather during their early stages, but extreme cold can stunt growth. By using high-yield, frost-resistant mustard varieties, farmers can achieve robust yields even under challenging conditions [20].

In the temperate climate of Kashmir, mustard cultivation requires varieties that can withstand cold temperatures, frost, and chilling injuries while delivering good yields. Below are some mustard varieties well-suited for Kashmir's conditions:

SS-II

Characteristics: Known for its resistance to chilling injuries and frost damage, SS-II is one of the improved varieties that farmers in Kashmir are increasingly adopting. It is also known for higher oil content and yield stability.

Maturity: Medium-duration.

Use: Primarily grown for oilseed production, with good potential for high returns.

COS 101

Characteristics: COS 101 is another cold-resistant variety gaining popularity in Kashmir. It performs well under cold and frost conditions, ensuring higher yields and more reliable crop survival.

Maturity: Medium-late duration.

Use: Cultivated for its oil content and resistance to frost.

PM-21

Characteristics: A cold-tolerant variety with high seed and oil yield, Pusa Mustard-21 is a preferred option for temperate climates. It has a strong resistance to frost and provides consistent yields.

Maturity: Early-maturing (85-90 days).

Use: Grown for oil extraction and suitable for cultivation in the colder regions of Kashmir.

RH-30

Characteristics: A variety that shows good adaptability to Kashmir's climatic conditions, RH-30 is moderately resistant to frost and offers good yields under temperate conditions.

Maturity: Medium duration.

Use: Preferred for oil production due to its high oil content.

These mustard varieties help ensure that farmers in Kashmir can secure better yields and returns while mitigating the risks posed by cold temperatures, frost, and chilling injuries during the Rabi season.

Fig 1 Sowing of seeds in rabi season: Preparing fields for a productive harvest in Kashmir

Table 1 Key Characteristics of cultivated rapeseed-mustard species (Cruciferous crops)

Common name	Botanical name	Days to maturity (Days)	Yield potential (Qtl/ha)	Oil content (%)
Indian mustard	*Brassica juncea*	120-150	12-20	40-44
Brown sarson	*Brassica campestris*	110-160	9-15	42-45
Yellow mustard	*Brassica rapa* var. *yellow sarson*	120-140	9-15	45-48
Black mustard	*Brassica nigra*	90-110	10-12	40-42
Gobhi sarson	*Brassica napus*	140-180	12-17	40-45

Impact of rapeseed-mustard species (Cruciferous crops)

Sulphur (S) is an essential nutrient for oilseed crops like mustard, playing a critical role in enhancing both yield and oil quality. Sulphur contributes to the synthesis of amino acids, proteins, and oil compounds in mustard, and deficiencies can significantly affect crop health and productivity [21]. Here's a summary of Sulphur's application in mustard and its impact on crop yield and oil content:

1. *Role of Sulphur in mustard growth and development*

Protein and amino acid formation: Sulphur is a key component of amino acids such as cysteine and methionine, which are vital for protein synthesis.

Enzyme activation: It activates enzymes involved in various metabolic pathways, enhancing the growth and vigor of mustard plants.

Chlorophyll formation: Essential for chlorophyll synthesis, promoting photosynthesis, which directly impacts yield.

2. *Impact on crop yield*

Improved plant growth: Sulphur application has been shown to improve plant height, leaf size, and the number of branches, which collectively increase photosynthesis and biomass.

Enhanced flowering and pod formation: Adequate Sulphur supports flower development and pod formation, resulting in a higher number of seeds per pod and an overall increase in seed yield.

Yield increase: Studies indicate that Sulphur application at the rate of 20-40 kg/ha can increase mustard seed yield by 15-30%, depending on soil Sulphur levels and environmental conditions [22].

3. *Impact on oil content and quality*

Increased oil percentage: Sulphur promotes the synthesis of oils and fats, and mustard crops supplemented with Sulphur often show a 1–3% increase in oil content compared to Sulphur-deficient crops [23].

Enhanced oil quality: It contributes to improved oil quality by increasing the concentration of beneficial fatty acids.

Sulphur and oil stability: Sulphur supports antioxidants, contributing to the stability and shelf life of the oil extracted from the seeds.

4. *Recommended application rates and methods*

Soil application: Generally applied at 20-40 kg/ha as elemental Sulphur or sulphate forms. The soil application before sowing allows for Sulphur availability throughout the crop cycle.

Foliar application: Foliar sprays of Sulphur can be used at critical growth stages, like flowering, to boost Sulphur uptake and enhance oil production further.

5. *Considerations for optimal use*

Soil testing: Testing soil for Sulphur levels can help determine the appropriate application rate and form, ensuring the crop's specific Sulphur requirements are met.

Integration with NPK fertilization: Applying Sulphur along with the recommended dose of nitrogen, phosphorus, and potassium (NPK) can maximize its impact on yield and oil content.

Stage-specific application: Applying Sulphur during early growth stages and before flowering can maximize its positive effects on mustard growth and oil accumulation [24].

Overall, Sulphur fertilization is a cost-effective practice that significantly impacts mustard yield and oil content, contributing to better returns and higher-quality oil production for farmers [25]. Sulphur's role in mustard is indeed multifaceted, impacting essential biochemical processes, from chlorophyll and oil synthesis to the formation of seed proteins, amino acids, enzymes, and glucosinolates. Its application can lead to substantial yield increases, ranging from 12-48% in irrigated and 17-124% in rainfed conditions, making it invaluable for optimizing mustard production [26-28].

Oats (Fodder)

Oats (*Avena sativa*) is another important Rabi crop in the Kashmir Valley, primarily grown for fodder to feed livestock. Oats are well-suited to the valley's cold environment, but prolonged frost periods and snowfall often pose challenges during the growing season. To ensure adequate fodder supply, farmers in Kashmir are adopting cold-tolerant oat varieties such as Sabzar, SFO-1 that are better equipped to withstand freezing temperatures and snow cover. Farmers in Kashmir are indeed turning to cold-tolerant oat varieties like Sabzar and SFO-1 to secure an adequate supply of fodder during the harsh winter months [29]. These varieties are specially bred to handle freezing temperatures and can thrive even under snow cover. This adaptation ensures that the farmers not only have a reliable fodder source during the cold season but also benefit from good yields, making these varieties a practical choice for sustaining livestock in the region's challenging winter conditions. Oats require good soil moisture for proper germination, and since the valley experiences periodic snowfall, it provides the necessary water. However, the intense cold can delay germination and limit the availability of fresh fodder. Improved oat varieties with frost tolerance are crucial for maintaining healthy fodder production and keeping livestock well-fed during the harsh winter months [30].

For the temperate conditions of Kashmir, oat (*Avena sativa*) varieties are selected for their adaptability to cold temperatures, frost resistance, and high fodder or grain yields. Oats are primarily grown for fodder in the region due to their ability to thrive in the colder climate. Here are some oat varieties well-suited for temperate Kashmir:

Sabzar

Characteristics: A popular oat variety in Kashmir, Sabzar is cold-tolerant and capable of withstanding freezing temperatures and snow cover. It provides high-quality fodder with good biomass yield.

Use: Primarily cultivated for fodder due to its nutritious forage.

SFO-1

Characteristics: This is another cold-tolerant variety favored by farmers in Kashmir. SFO-1 can withstand frost and is known for its high green fodder and dry matter production, making it a reliable option for livestock feed.

Use: Grown for fodder, especially during the winter months.

Kent

Characteristics: A well-known variety for its cold tolerance, Kent is widely grown in temperate climates. It is a high-yielding variety, producing both grain and fodder, with good resistance to cold and frost.

Use: Suitable for both grain and fodder production.

OS-6

Characteristics: This variety is highly adaptable to colder regions and can withstand frost. OS-6 produces high green fodder and dry matter yields, making it a good choice for Kashmir's climate.

Use: Primarily cultivated for fodder.

HFO-114

Characteristics: A high-yielding variety with good tolerance to cold temperatures, HFO-114 is known for producing high-quality forage. It can handle the cold, snowy winters in Kashmir.

Use: Grown for fodder.

KO-1

Characteristics: KO-1 is an oat variety that is well-suited for colder regions. Released for its adaptability to the local agro-climatic conditions, KO-1 offers good resistance to common diseases.

Use: Provides high nutritional value for livestock.

These oat varieties are chosen by farmers in Kashmir to ensure a reliable supply of fodder during the harsh winter months. Their ability to thrive in cold, frost-prone conditions while providing high yields makes them essential for sustaining livestock in the region.

Peas

Peas (*Pisum sativum*) are a popular Rabi crop grown in the Kashmir Valley due to their high nutritional value and market demand. However, like other crops, peas are vulnerable to the valley's prolonged cold spells. Frost-resistant varieties of peas have become essential in mitigating the damage caused by extended frost periods, ensuring higher yields and preventing crop loss [31]. Peas are typically sown in mid to late October, but unpredictable weather, such as sudden frost or snowfall, can severely impact their growth. The development of high-yield pea varieties that can flourish even under low temperatures is a game-changer for farmers in the valley, helping them maximize returns despite the region's cold climate [32]. In temperate conditions like those found in Kashmir, certain pea (*Pisum sativum*) varieties are well-suited for cultivation, especially during the Rabi season. These varieties are selected for their adaptability to the cooler climate, frost tolerance, and high

yields [33-35]. Some of the commonly recommended pea varieties for Kashmir include:

Arkel

Maturity: Early maturing (about 60-65 days).

Characteristics: It is a dwarf variety with high yields and sweet, tender pods. Arkel is preferred for early sowing in temperate climates and has good tolerance to cold.

Use: Mainly grown for fresh market and kitchen gardening.

AP-3

Maturity: Medium duration (65-70 days).

Characteristics: AP-3 is a widely grown variety in Kashmir known for its high yield potential and good quality pods. It is moderately resistant to frost.

Use: Suitable for fresh consumption and canning purposes.

Bonneville

Maturity: Mid-season (75-80 days).

Characteristics: This variety produces large, smooth peas with good flavor and is relatively cold-tolerant, making it ideal for Kashmir's temperate conditions.

Use: Primarily grown for fresh market and processing.

Azad P-1

Maturity: Early maturing (55-60 days).

Characteristics: This is an early-maturing pea variety with high yields and good cold tolerance. It is suitable for early sowing in cold conditions.

Use: Primarily for fresh market.

VL Matar-42

Maturity: Medium duration (60-65 days).

Characteristics: This variety is suitable for cold climates and has good resistance to frost. It produces high yields with uniform, well-filled pods.

Use: Fresh market and processing.

PB-89

Maturity: Late maturing (80-85 days).

Characteristics: It has good tolerance to low temperatures and provides excellent yields of large, high-quality peas.

Use: Fresh market and suitable for canning.

These varieties help farmers in Kashmir meet the demands of both fresh consumption and processing industries while ensuring good productivity under cold conditions.

Garlic

Garlic (*Allium sativum*), a principal crop in the region, is widely cultivated during the Rabi season due to its high demand both locally and in markets across India. However, the freezing temperatures and frost conditions prevalent in the Kashmir Valley during winter make garlic cultivation a challenging endeavor. Frost-resistant garlic varieties are essential for ensuring that the crop can survive the harsh winter and develop properly by the time spring arrives [36]. Garlic is typically sown in late September or early October to give it enough time to establish before the severe cold sets in. Despite the challenges, garlic is one of the most lucrative crops for farmers in the valley, especially when grown using improved varieties that are more resilient to frost and low temperatures [37]. In temperate regions like Kashmir, garlic is widely grown due to its adaptability to cooler climates. SKUAST-Kashmir (Sher-e-Kashmir University of Agricultural Sciences and Technology) has released several garlic varieties suitable for temperate conditions in Kashmir. Here are some notable ones:

Kashmir local garlic

This variety is well-adapted to the local agro-climatic conditions and is known for its good flavor and storage qualities.

KG-1

Released for its high yield potential and good bulb quality, KG-1 is adapted to the temperate climate of Kashmir and is known for its disease resistance.

KG-2

This variety offers improved yield and quality traits compared to traditional local varieties. It is suitable for cultivation in the temperate regions of Kashmir.

SKUAST-K garlic

This variety was developed specifically for the hilly and temperate regions, focusing on yield, bulb size, and resistance to common garlic diseases.

These varieties have been developed through extensive research and breeding programs to ensure they meet the specific climatic and agronomic conditions of temperate Kashmir, providing farmers with options that enhance yield and quality.

Fig 2 Sowing seeds: Farmers begin cultivation for the rabi season in Kashmir Valley

Challenges of harsh climatic conditions

The Kashmir Valley faces some of the harshest winter conditions, posing significant challenges to its agriculture. With winter temperatures dropping well below freezing, the region undergoes long spells of chilling and frost, lasting several months and affecting both crop and livestock management. Heavy snowfall, which can reach several feet in some areas, blankets fields, restricting access to arable land and often delaying sowing and transplanting of cold-tolerant crops. These prolonged freezing temperatures cause critical issues for crop growth and development. Seed germination is often delayed or halted as the soil remains too cold, preventing seeds from breaking dormancy. Even if germination occurs, seedlings may grow stunted due to insufficient warmth and sunlight, leading to slow and uneven crop establishment. Reduced growth rates and poor root development mean plants struggle to absorb nutrients effectively, ultimately impacting yields [38-40].

The intense cold also affects livestock health and productivity. Animals are kept indoors for extended periods, increasing the need for feed and forage, which becomes scarce as pastures are inaccessible or covered with snow. Dairy production often declines as the animals expend more energy maintaining body temperature, and respiratory illnesses become more common in the damp, cold environment [41]. Consequently, farmers in the Kashmir Valley require additional resources, knowledge, and support to adopt winter-resistant crop varieties and efficient livestock management practices, making it possible to maintain productivity even under these challenging conditions [42-43]. Enhancing training programs and providing necessary inputs, such as cold-hardy crop varieties and tailored livestock management solutions, can help maintain productivity even during harsh winter months.

Frost damage: Frost is one of the most common threats to Rabi crops, particularly during the early stages of growth. If not properly managed, frost can kill young plants or severely stunt their growth.

Prolonged snow cover: The valley often receives heavy snowfall, which can cover the crops for extended periods, reducing the amount of sunlight they receive and delaying their growth. This prolonged soil freeze creates a nutrient uptake issue as well. Even though the soil may contain ample nutrients, the low temperatures slow down microbial activity, reducing the breakdown of organic matter into plant-available forms. Thus, plants are deprived of both water and nutrients, critical for early growth stages, leading to delayed development, weakened root systems, and reduced resilience against environmental stresses [44].

Soil moisture issues: While snowfall helps maintain soil moisture, excessive cold can cause the soil to freeze, making it difficult for roots to absorb water and nutrients. Snowfall in the Kashmir Valley serves as a natural reservoir for soil moisture, which becomes particularly valuable during the growing season. As snow melts gradually in spring, it replenishes groundwater and keeps the soil moist, providing essential water to crops as they resume growth after winter dormancy [45]. However, the extreme winter cold can cause issues that complicate this otherwise beneficial process. When temperatures drop significantly, the soil can freeze deeply, especially in open fields exposed to chilling winds. Frozen soil forms a hard crust that restricts root activity, as the roots are unable to penetrate the hardened soil layers or absorb water effectively. In this frozen state, moisture, although present, becomes inaccessible to plants, as it remains locked within the soil structure [46].

When thawing finally begins, the sudden influx of water from melting snow can lead to oversaturation of the soil. This excess moisture may increase the risk of root rot or other soil-borne diseases, further challenging the recovery and productivity of crops. To address these challenges, agricultural practices in Kashmir increasingly focus on selecting cold-resistant crop varieties, employing soil amendments, and using protective mulches to mitigate the adverse effects of freezing temperatures on soil and crop health [47-49].

Need for improved varieties for higher returns

In the Kashmir Valley, agriculture faces an intense set of challenges due to extended periods of frost, sub-zero temperatures, and heavy snowfall that can stretch across several months. These harsh winters often hinder crop growth by delaying germination, stunting plant development, and reducing overall productivity. Traditional crop varieties, while resilient in many ways, often lack the genetic adaptations necessary to withstand prolonged cold spells, resulting in lower yields and increased risk of crop failure [50].

To address these conditions, agricultural research institutions and local agricultural departments are focusing on the development and promotion of cold-tolerant and frost-resistant crop varieties specifically suited for the Valley's extreme climate. These improved varieties are bred to adapt to frigid environments and have a genetic resistance to chilling injuries, frost damage, and even sub-zero temperatures. For instance, cold-tolerant oat varieties such as Sabzar and SFO-1 and improved mustard varieties like SS-II and COS 101 are already gaining traction among farmers. These crops not only endure low temperatures but also maintain their growth cycle, enabling them to germinate, mature, and yield despite adverse winter conditions [51-52].

Additionally, these enhanced varieties are often designed to mature within a shorter growing season, which is crucial in the Valley where the viable cultivation period is limited. Their faster development rate enables them to establish strong root systems and initiate flowering before the onset of peak winter, thus optimizing their yield potential [53].

Adopting these improved varieties has benefits beyond yield stability. Cold-resistant and frost-tolerant varieties reduce the need for supplementary interventions, such as artificial frost protection and greenhouse cultivation, which can be costly and labor-intensive. With resilient crop varieties, farmers in Kashmir are better able to secure reliable harvests, improve food security, and achieve greater economic stability in the face of increasingly variable winter climates [54].

This shift toward improved varieties aligns with broader goals in sustainable agriculture, allowing for higher productivity per unit area without overburdening the environment or increasing dependency on costly inputs. Embracing these advancements is crucial for enhancing the resilience of the Valley's agriculture sector and ensuring that crop production remains viable even in the face of challenging winter conditions [55]. To combat the challenges posed by the valley's frost conditions and harsh winters, there is an increasing need for the adoption of improved crop varieties. These varieties are bred to be frost-resistant, cold-tolerant, and capable of producing higher yields despite the region's extreme weather.

Frost-resistant varieties: Crops like mustard, oats, peas, and garlic can thrive in the valley's conditions when farmers utilize varieties that are specifically designed to withstand prolonged frost and freezing temperatures.

High-yielding varieties: Improved varieties not only resist the cold but also offer higher yields, ensuring that farmers can achieve better economic returns even when faced with difficult growing conditions.

Shorter growing cycles: Many of these improved varieties have shorter growing cycles, allowing them to mature faster and reduce the risk of being exposed to extreme cold for prolonged periods.

CONCLUSION

The cultivation of Rabi crops in the Kashmir Valley exemplifies the resilience and adaptability of local agriculture in response to the region's temperate challenges. Despite facing prolonged winters, frost, and heavy snowfall, Kashmiri farmers

have progressively adapted by selecting cold-resistant varieties, employing precise sowing techniques, and optimizing nutrient applications, such as sulfur for mustard. Improved mustard varieties, like SS-II and COS 101, alongside cold-tolerant oats such as Sabzar and SFO-1, demonstrate significant yield stability and resilience under Kashmir's distinct winter conditions, ensuring both food security and economic stability. Saffron cultivation in Pampore continues to hold a unique cultural and economic importance, adding another layer of complexity and value to the Rabi season. The continued adaptation in crop variety selection, nutrient management, and cultivation techniques has allowed the Kashmir Valley to maintain agricultural productivity while addressing the vulnerabilities posed by its challenging climate. These practices not only contribute to sustainable agricultural development but also secure local livelihoods and fortify the region's agrarian economy, offering a model of adaptation in temperate agro-ecosystems. Future efforts to enhance irrigation resources, refine cold-resistant crop varieties, and integrate climate-resilient practices will further strengthen Rabi crop cultivation in the Kashmir Valley, ensuring its sustainability and economic viability amid evolving climatic conditions. Harsh winters with prolonged frost, deep snow cover, and freezing temperatures present significant challenges to agriculture, often hindering crop germination, growth, and yield. Traditional crop varieties struggle under these conditions, limiting productivity and increasing vulnerability to crop failure. However, the development of frost-resistant, cold-tolerant, and high-yielding varieties, such as specific mustard and oat strains, offers promising solutions. These improved varieties are tailored to withstand the valley's extreme climate, supporting reliable harvests, enhanced food security, and higher economic returns. By adopting these resilient crops, Kashmir's farmers can optimize productivity and sustain agriculture despite the region's challenging winter conditions. The resilient cultivation of Rabi crops, marked by the adoption of cold-tolerant varieties, tailored cultivation techniques, highlights local agriculture's capacity to adapt and thrive amid harsh winter conditions, ensuring food security, economic stability, and a model for sustainable farming in temperate agro-ecosystems.

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