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Climate Change and Insect Population Dynamics in Balochistan: Implications for Pest Management, Pollinator Conservation, and Agroecosystem Resilience

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ABSTRACT

As one of the largest and physiographically most heterogeneous regions of Pakistan, Balochistan is increasingly vulnerable to the compounded impacts of climate change, including rising temperatures, altered precipitation regimes, recurrent flooding and intensifying heatwaves. These climatic shifts are driving insects along novel ecological trajectories with substantial consequences for agricultural productivity and ecosystem services. In the warmer lowland regions of Makran, Kharan and Nasirabad, elevated night-time temperatures and prolonged drought conditions are enhancing pest survival and reproductive potential, whereas episodic extreme heatwaves can suppress insect fecundity and impair the efficacy of natural enemies. In contrast, upland areas with historically strong cold constraints, such as Quetta, Kalat and Zhob, are experiencing pest range expansions and increased voltinism, while cold-adapted pollinators, including bumble bees, are declining due to warming-induced habitat loss. Major flooding events, particularly the record-breaking floods of 2022, have further altered insect dynamics by eliminating some ground-dwelling pest populations, facilitating the emergence of larval vectors and destroying ground-nesting pollinator habitats. Heatwaves exacerbate these disturbances by disrupting insect reproductive physiology, reducing nectar and pollen quality and diminishing pollination services for crops such as date palm, mango and vegetables. Collectively, these processes are contributing to more frequent pest outbreaks, rapid pollinator declines and weakened biological control, thereby threatening food security and rural livelihoods in Balochistan. Addressing these challenges requires climate-sensitive integrated pest management, restoration of pollinator habitats and flood-adaptive farming practices, supported by region-specific monitoring, multidisciplinary research and farmer-centered policy frameworks.

INTRODUCTION

Balochistan, the largest province of Pakistan, is ecologically vulnerable and climatically heterogeneous due to the coexistence of coastal zones, arid deserts and mountainous landscapes[1]. This environmental mosaic supports diverse agroecosystems, including date palm plantations, cereal cropping systems, fruit orchards and rangeland-based livestock production; however, it also heightens exposure to climatic extremes such as prolonged droughts, severe heatwaves and destructive flooding[2]. Recent climatic assessments indicate that the region is experiencing increased temperature variability, highly erratic precipitation patterns and compounding climate risks, all of which exert strong influences on insect population dynamics[3]. The 2022 monsoon floods caused widespread destruction of crops and rural livelihoods, while unprecedented pre- and post-monsoon heatwaves across South Asia were estimated to be thirtyfold more likely under anthropogenic warming[4].

These shifts in climatic regimes are fundamentally altering insect population dynamics, pest outbreak frequencies, pollination services and the effectiveness of biological control, thereby posing serious threats to food security and agroecosystem resilience in Balochistan[5]. At the global scale, climate change is now recognized as one of the dominant drivers shaping insect distribution, abundance and species interactions[6]. As ectotherms, insects are particularly sensitive to thermal and hydrological variation and often respond through changes in phenology, increased or altered voltinism, geographic range shifts and modified predator-prey or plant-pollinator interactions[7]. These responses are highly heterogeneous: in some cases, insect pests benefit from accelerated development, enhanced overwinter survival and prolonged activity periods under warming and moderate hydrological stress[8], whereas in other instances populations decline or become nonviable when thermal or flood extremes exceed physiological tolerances[9].

Understanding these dynamics is especially urgent in Balochistan, where cooler highland regions and already warm lowland systems are expected to exhibit contrasting responses in pest pressure, pollination services and biological control potential[5]. In warmer lowland areas such as the Makran, Kharan and Nasirabad divisions, rising temperatures have generally favored pest survival and reproductive success[2]. Elevated night-time temperatures further stimulate insect growth and increase the number of generations per year[10], while drought-stressed crops are particularly susceptible to sap-sucking pests such as whiteflies and Dubas bugs[11]. Nevertheless, the increasing frequency of extreme heatwaves under climate change can suppress insect populations by reducing survival, mating success and fertility-especially in males-resulting in delayed reductions in reproductive output weeks after exposure[12]. Such effects have been documented across insect pests and associated trophic groups, where climatic variability and thermal stress can drive pronounced boom-bust population dynamics[13]. Moreover, heatwaves complicate pest management by reducing pesticide efficacy through volatilization and by undermining the performance of parasitoids and predators that are essential for sustainable pest regulation[14].

In the cooler upland regions of Quetta, Kalat and Zhob, climate change has relaxed historical cold constraints on many insect pests, enhancing overwinter survival and permitting multiple generations within habitats that were previously climatically restrictive[15]. This shift has resulted in elevated pest pressure on high-altitude orchards and rangeland systems. Comparable upslope range expansions have been documented for several insect taxa in mountainous ecosystems worldwide[16], posing significant risks to horticultural crops such as apples, cherries and grapes in Balochistan[5]. However, not all insects benefit from warming trends; cold-adapted species-particularly specialized pollinators such as bumble bees-are experiencing range contractions and reduced fitness as rising temperatures push them beyond their ecological tolerances[17]. Declines in pollinator abundance subsequently reduce pollination services in highland orchards and increase the likelihood of phenological mismatches between crop flowering and insect activity[18]. Table 1 summarizes the contrasting effects of climate change on insect dynamics in warmer lowlands and cooler uplands, highlighting increased pest survival, voltinism and range expansion under warming conditions, alongside concurrent declines in pollinators and natural enemies across both zones. These trends collectively impair ecosystem services and threaten key crops, including date palm, mango, cereals, apples, grapes and cherries[19].

Flooding represents another critical climatic driver shaping insect population dynamics. In 2022, extensive flooding across Balochistan caused severe damage to crops and created prolonged standing water in agricultural landscapes[10]. While these conditions suppressed certain soil-dwelling pest species, they simultaneously facilitated the proliferation of disease vectors-particularly mosquitoes and sandflies-thereby increasing the risk of malaria and leishmaniasis outbreaks in rural communities[2]. Ground-nesting pollinators were also adversely affected, as floodwaters destroyed nesting habitats, leading to declines in bee diversity and delays in the recovery of pollination services within agroecosystems[21]. Although, some insect populations may rebound rapidly following floods due to elevated humidity and disrupted cropping calendars, the

Table 1: Impacts of climate change on insects in warm vs. cool regions of Balochistan

Climate zone	Pest dynamics	Pollinator dynamics	Natural enemy dynamics	Example of affected crops	Citations
Warm lowlands (Makran, Kharan, Nasirabad)	More pest generations, higher survival, drought-stressed crops vulnerable	Heat stress reduces bee activity, flower-pollinator divergence	Parasitoids/predators declining beneath high heat	Date palm, mango, cereals	Abid et al.,[2]
Cool uplands (Quetta, Kalat, Zhob)	Cold limitations relaxed, pests expanding upslope	Cold-adapted pollinators (e.g., bumble bees) declining	Range shifts disrupting balance	Apples, grapes, cherries	Nielsen et al.,[18]

Table 2: Effects of climate extremes on insect populations in Balochistan

Climate driver	Pest response	Pollinator response	Natural enemy response	Citations
Floods	Soil pests repressed; mosquito/sandfly outbreaks rise	Ground-nesting bees damaged, delayed recovery	Habitat loss affects parasitoids	Govt. of Pakistan et al[20]
Heatwaves	Male sterility, suppressed reproduction	Colony collapse risk, reduced foraging	Lower biocontrol efficiency	Harvey et al.[22]
Drought	Crop stress favors sap-sucking pests	Floral lack reduces pollinator diversity	Reduced prey availability	Martinet et al..[24]
Warming trends	More generations, overwintering survival	Range shifts, phenology mismatches	Transformed predator-prey dynamics	Chen et al.[9]

broader ecological consequences are typically destabilizing, with increased risks of pest outbreaks and pollination failures following hydrological extremes[3].

Extreme heatwaves represent an additional and increasingly critical stressor in insect ecology[22]. Even when direct mortality is minimal, short-term exposure to extreme temperatures can severely impair male fertility well below lethal thresholds, resulting in substantial reductions in reproductive output[23]. Pollinators are particularly vulnerable to heat stress, as colony-level thermoregulation entails high metabolic costs and often fails during multi-day heatwave events, leading to brood mortality and reduced foraging activity[24]. These pollination deficits threaten both yield and quality of crops that flower during the hot pre-monsoon season in Balochistan, including mango, date palm and a range of vegetable crops[25]. In addition to reducing floral longevity, heat stress diminishes the nutritional quality of nectar and pollen, thereby amplifying the negative impacts of pollinator declines on agricultural productivity[26]. Table 2 synthesizes the effects of climate extremes on insect populations in Balochistan, demonstrating that floods, heatwaves, droughts and long-term warming differentially influence pest, pollinator and natural enemy dynamics[27]. While pest species frequently benefit through increased voltinism and outbreak potential, pollinators and natural enemies generally experience reductions in activity, diversity, or functional efficiency, collectively weakening ecosystem resilience and crop productivity[28].

These climate-induced pressures rarely act in isolation. Instead, interacting extremes-such as combined heat, drought and flood regimes-generate nonlinear responses that are difficult to predict using single-factor frameworks[29]. The Southwest Asian desert locust outbreak of 2019-2020, linked to anomalous cyclonic activity in the western Indian Ocean, exemplifies how regional climatic anomalies can synchronize favorable conditions for pest proliferation across vast areas, exceeding the capacity of conventional monitoring and control systems[30]. Balochistan remains particularly ecologically vulnerable due to limited pest surveillance infrastructure, rendering the region highly susceptible to climate-driven pest shocks[31].

The implications of these interacting stressors for pest management, pollination services and agroecosystem resilience in Balochistan are profound. Climate-intelligent approaches are required, incorporating degree-day modeling, dynamic action thresholds and biological control agents capable of maintaining efficacy under variable thermal and moisture regimes[32]. Habitat-based strategies to enhance pollinator resilience, including the restoration of floral resources and the provision of nesting refugia, can mitigate heatwave-induced mortality and post-flood habitat loss[33]. Furthermore, flood-adaptive farming practices-such as raised beds, improved drainage and flexible sowing calendars-together with accessible climate services and early warning systems for farmers, are essential to strengthening agroecosystem resilience[34]. In the absence of such anticipatory measures, the interacting effects of warming, flooding and heatwaves are likely to continue reducing crop productivity and destabilizing pest regulation and pollination services in this already highly sensitive province[35].

Overall, climate change is driving profound shifts in insect ecological dynamics across Balochistan, with pest species generally increasing in abundance in both warming lowland and moderating highland environments, while pollinators tend to decline under combined heat and flood stress and natural enemies are increasingly suppressed by climatic extremes[36]. These alterations threaten not only the effectiveness of pest regulation but also the broader ecosystem services that underpin agricultural production and rural livelihoods[37]. Addressing these challenges will require multidisciplinary research, region-specific surveillance systems and adaptive policy frameworks that integrate entomology and climatology with active farmer engagement, thereby enhancing the resilience of Balochistan's agroecosystems under accelerating climate change[38].

Climate profile of Balochistan: Balochistan, the largest province of Pakistan, encompassing approximately 44% of the country's total land area, is characterized predominantly by arid to semi-arid climatic conditions[39]. The province receives very low annual precipitation, typically ranging from about 50 mm in arid zones to around 250-300 mm in relatively wetter areas and is highly dependent on irregular winter and monsoonal rainfall[40]. Summers are extremely harsh, with temperatures in lowland regions frequently exceeding 45°C, whereas winters in highland areas such as

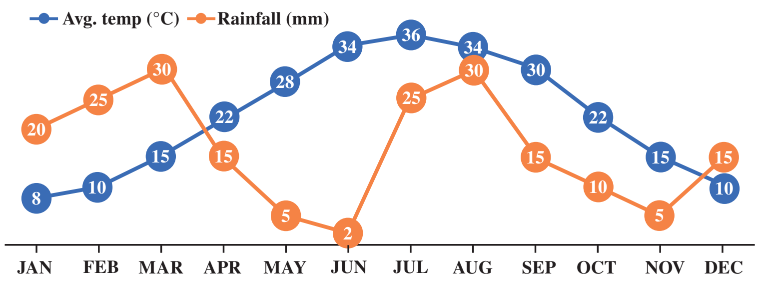

Fig. 1: Climate profile of Balochistan

Quetta are often severe, with temperatures commonly falling below freezing[41]. Such pronounced climatic extremes pose substantial ecological risks to sensitive biological communities, particularly insect populations[42].

Balochistan exhibits marked topographical heterogeneity, ranging from coastal plains and river basins to mountainous highlands, resulting in diverse microclimatic zones that strongly influence insect distribution, phenology and behavior[43]. Over recent decades, persistent increases in temperature and significant declines in precipitation have accelerated desertification processes, reduced vegetation cover and degraded natural and agricultural habitats[44]. Meteorological records indicate that the province has experienced an increase of approximately 0.6-1.0°C in mean annual temperature over the past 50 years, accompanied by a rising frequency of heatwaves and prolonged drought events[45]. Figure 1 illustrates the climatic profile of Balochistan, highlighting the contrast between warm lowlands and cooler uplands, extreme aridity, high thermal variability and erratic rainfall patterns that collectively exert strong influences on insect population dynamics and crop productivity in the region[46].

These climatic changes have direct and indirect effects on insect population dynamics across Balochistan. Prolonged dry seasons reduce the availability of floral resources and host plants, adversely affecting pollinators such as bees and butterflies[47]. In contrast, several insect pests-including aphids, whiteflies and grasshoppers-are able to persist and even thrive under drought-induced stress due to weakened plant defenses and reduced pressure from natural enemies[48]. Moreover, warmer winter conditions enhance the overwintering survival of many pest species and extend their active periods, resulting in increased voltinism and higher population growth rates[23]. Climate-driven warming has also facilitated the northward and altitudinal expansion of several insect species within the province. Pest species formerly restricted to warmer lowland regions are now increasingly recorded in cooler upland agricultural zones, where they pose emerging threats to high-value crops such as apples, pomegranates and grapes cultivated in areas including Kalat, Mastung and Ziarat[49].

Extreme weather events, including intense rainfall episodes and frost occurrences, further disrupt insect reproductive cycles and larval development, leading to sharp population declines or, conversely, unexpected outbreaks of varying magnitude and timing[50]. Despite increasing evidence of observed and projected climatic impacts, the lack of long-term insect monitoring programs in Balochistan remains a major limitation. This data deficiency constrains the capacity of researchers and policymakers to anticipate pest epidemics, understand ecological disturbances and develop region-specific, climate-responsive insect management strategies.

Effects of climate change on major insect groups in Balochistan: The impacts of climate change on insect assemblages in Balochistan are highly heterogeneous, reflecting differences in ecological function, physiology and life-history strategies among taxa[51]. Three insect groups are of particular importance in regional agroecosystems: agricultural pests, pollinators and natural enemies[52]. Together, these groups play critical roles in sustaining agricultural productivity and shifts in their population dynamics can substantially influence crop yields, food security and ecosystem stability across the province[53]. Ongoing climatic changes are restructuring the distribution, abundance and interactions of major insect groups in Balochistan, with pest species exhibiting increased voltinism and expanded geographic ranges, pollinators experiencing population declines and phenological mismatches with flowering plants and natural enemies undergoing weakened predator-prey interactions. Collectively, these trends destabilize agroecosystems and contribute to reduced crop productivity[54].

Agricultural pests: Climate change has markedly altered pest dynamics in Balochistan by influencing their spatial distribution, developmental rates, generation frequency and outbreak intensity[55]. Heatwaves, in particular, promote increased voltinism, facilitate geographic range expansion and reduce overwinter mortality in many pest species[56]. For example, populations of the date palm pest *Ommatissus lybicus* in southern Balochistan have responded to warming

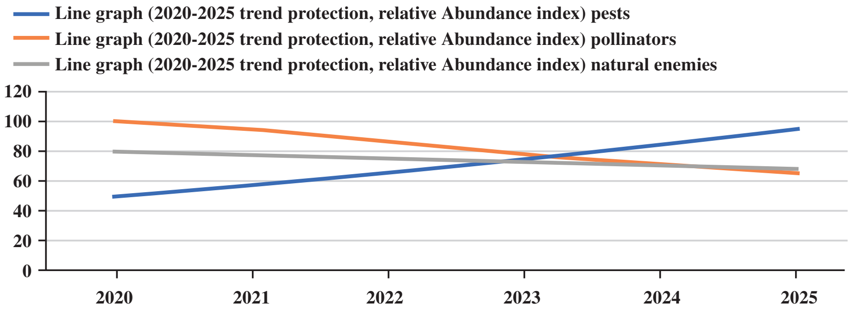

Fig. 2: Line graph (2020–2025) trend projection, relative abundance index
(Case Studies from Balochistan and Comparable Arid Regions)

temperatures and drought conditions by exhibiting enhanced reproductive activity and expanded distributional ranges[57]. Similarly, outbreaks of whiteflies (*Bemisia tabaci*), aphids and thrips have become more frequent and severe, especially in arid and semi-arid agricultural zones such as Turbat and Panjgur. These pests cause significant direct damage to crops and also function as vectors of economically important plant viruses[58].

High temperatures and prolonged dry conditions further suppress the effectiveness of natural enemies by shortening their active periods and reducing their regulatory capacity, thereby allowing pest populations to proliferate. In addition, reduced rainfall increases host plant susceptibility to herbivory, as water stress compromises plant vigor and defensive capacity[21].

Pollinators: Bees (*Apis* spp.) but terflies and solitary bees play a critical role in the production of fruit crops such as apples, almonds, pomegranates and melons, which are of major economic importance in Balochistan[59]. Despite their importance, these beneficial insects are increasingly threatened by climate-driven shifts in floral phenology, habitat degradation and physiological stress associated with prolonged drought and elevated temperatures[60]. Nutritional stress and population declines in pollinators are closely linked to reductions in the abundance and diversity of flowering plants during extended dry periods[61]. Phenological mismatches, whereby the activity periods of insect pollinators become decoupled from the flowering times of host plants due to warming, have been documented in comparable dryland ecosystems and are increasingly evident in the highlands and orchard systems of Balochistan[62]. In addition, the intensified use of pesticides in response to rising pest outbreaks further exacerbates pollinator declines, compounding the stress imposed by adverse climatic conditions[61].

Natural enemies (biological control agents): Natural enemies, including predatory lady beetles (Coccinellidae), lacewings (Chrysopidae), parasitoid wasps and entomopathogenic fungi, provide essential pest regulation services in the cropping systems of Balochistan[63]. However, their abundance, activity and functional performance are highly sensitive to climatic perturbations. Rising temperatures and declining humidity can suppress parasitoid activity and slow the development and infectivity of entomopathogenic pathogens[64]. For example, multiple studies have demonstrated that heat stress reduces foraging efficiency and oviposition rates in parasitoid wasps, including *Trichogramma* spp., which are widely used for the biological control of lepidopteran pests in orchard systems[65]. Drought-induced stress may also alter host-predator interactions, rendering pest species less detectable or less accessible to their natural enemies[52].

Disruptions to biological control services often lead farmers to increase reliance on synthetic pesticides, thereby elevating production costs and accelerating the risk of resistance development. Figure 2 presents selected case studies that provide empirical evidence of how climate change has already begun to influence insect population dynamics in Balochistan and comparable arid regions[66]. The limited availability of long-term ecological monitoring data in Balochistan necessitates reliance on short-term studies, farmer reports and extrapolations from ecologically similar regions such as southern Iran, Oman and the Rajasthan region of India. The following section synthesizes key examples of insect pest, pollinator and natural enemy responses to climate variability[67]. Previous studies report similar patterns of increasing pest pressure, declining pollinator populations and reduced effectiveness of natural enemies under climate stress, indicating that the observed changes in insect communities in Balochistan are part of broader trends affecting dryland ecosystems globally[68].

Desert locust outbreaks in Balochistan: Desert locust (*Schistocerca gregaria*) outbreaks have increasingly positioned Balochistan as one of the provinces most vulnerable to climate-driven pest risks[69]. Nearly two-thirds of the province provides ecologically suitable breeding conditions for locusts and the 2019-2020 invasion clearly

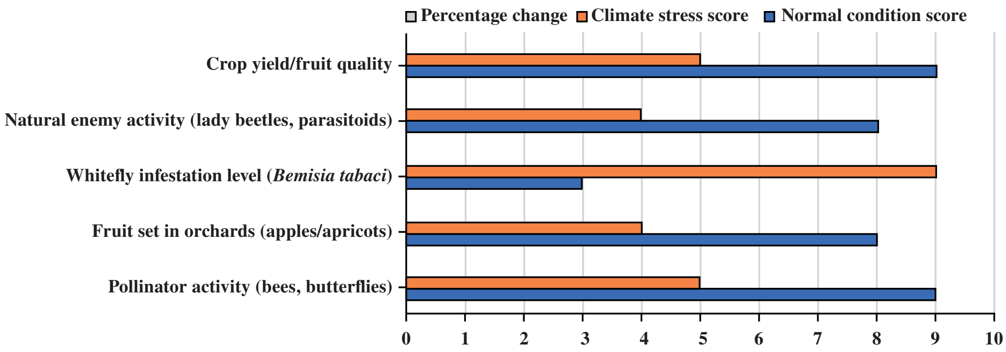

Fig. 3: Climate change impacts on insect dynamics

demonstrated how climate variability amplifies the likelihood and severity of pest outbreaks[30]. Unusually intense cyclonic rainfall associated with Cyclone Mekunu (2018) and Cyclone Luban (2018) across the Arabian Peninsula created optimal breeding environments, leading to the formation of large swarms that subsequently migrated into Balochistan and caused extensive crop damage in districts such as Nushki, Chaghi and Khuzdar. Empirical studies have shown that locust population growth is strongly promoted by increased rainfall, elevated soil moisture and favorable temperature regimes, which together exhibit a direct positive relationship with swarm formation and rapid population expansion[70]. These outbreaks underscore how climate-induced weather anomalies pose serious threats to food security in arid regions such as Balochistan.

Aphid infestations on wheat and barley: Among cereal crop pests, aphids (*Sitobion avenae* and *Rhopalosiphum padi*) have exhibited pronounced interannual variability in population dynamics in Balochistan in response to climatic fluctuations[71]. Field studies conducted in the Quetta and Pishin valleys have documented significantly higher aphid densities during years characterized by milder winters and warmer spring conditions, which enhance aphid survival and reproductive capacity[67]. Comparable observations reported by farmers indicate that late-season cold spells and abrupt temperature fluctuations often coincide with aphid outbreaks, resulting in substantial yield losses in wheat and barley. Climatic warming has not only facilitated aphid population growth but has also extended their active periods, thereby intensifying crop damage across the cereal-producing regions of Balochistan[72].

Dubas bug (*Ommatissus lybicus*)
A growing pest in date palm orchards: The Dubas bug (*Ommatissus lybicus*), one of the most destructive pests of date palm, has been reported with increasing frequency and severity in the Turbat and Panjgur districts of Balochistan[53]. Previously restricted largely to lower latitudes characterized by hot and dry climates, this pest has expanded its seasonal activity and is now increasingly observed in orchards where it was formerly uncommon[73]. Rising winter temperatures have enhanced overwintering survival, while water scarcity and heat-stressed date palms have become more susceptible to feeding and oviposition[69]. Sap-feeding by Dubas bugs causes leaf yellowing and fruit drop, directly reducing yield, while honeydew excretion promotes the growth of sooty molds that impair photosynthetic efficiency[74]. Farmers report that pesticide applications are now required earlier in the season and at higher frequencies than in previous decades. This trend is consistent with findings from Oman and the United Arab Emirates, where similar climatic shifts have triggered earlier pest emergence and increased population densities of *O. lybicus*[75].

Climate change impacts on pollinators, pests and natural enemies: Figure 3 illustrates the impacts of climate change on insect population dynamics in Balochistan. Climate variability is restructuring insect-plant-natural enemy interactions across the province, with significant consequences for fruit and vegetable production systems[37]. Declines in the activity of wild bees during spring flowering periods have been documented in highland orchards of Ziarat, Kalat and Mastung[76]. These declines are attributed to warmer winter temperatures and erratic spring rainfall, which disrupt synchrony between crop flowering and pollinator emergence[6]. Reduced pollination directly affects fruit set, particularly in crops such as apples and apricots that are highly dependent on insect-mediated pollination. Comparable trends have been reported from Mediterranean desert ecosystems, where wild pollinators show moderate to high sensitivity to prolonged drought and habitat loss[77]. In Balochistan, these challenges are further exacerbated by declining floral diversity and increased exposure to pesticides from adjacent agricultural fields. In the absence of established pollinator surveillance systems, the agricultural consequences of pollinator losses are reflected in reduced yields and diminished fruit quality[78].

Vegetable-producing regions such as Khuzdar, Nushki and Lasbela are also experiencing increasing infestations of the whitefly *Bemisia tabaci*[79]. Once considered a predominantly seasonal pest, *B. tabaci* has become a persistent and recurring threat to crops including tomato, chili and okra[80]. Farmers report that warmer autumn conditions and prolonged drought reduce the abundance of natural enemies while extending the reproductive period of whiteflies[37], resulting in earlier onset and longer duration of outbreaks. Similar pest behavior has been observed in Rajasthan and southern Iran, where elevated temperatures enhance whitefly fecundity, shorten developmental periods and increase the transmission of plant viruses, particularly Tomato yellow leaf curl virus[81].

In Balochistan, limited access to predictive pest management tools compels smallholder farmers to rely heavily on broad-spectrum pesticides, which further suppress populations of beneficial insects[82]. Concurrently, the activity of natural enemies in orchard and agroecosystems has declined, with reductions reported in populations of lady beetles, parasitoid wasps and other predatory arthropods under changing environmental and management conditions[83]. This decline is driven by phenological mismatches between predators and prey, exposure to temperatures exceeding optimal physiological thresholds and residual pesticide effects. Experimental and field studies from arid environments demonstrate that even modest climatic shifts can significantly impair the foraging efficiency and reproductive capacity of natural enemies[84]. Supporting evidence from Egypt and Tunisia further indicates that climate-induced phenological mismatches in parasitoid-host systems enable pests to escape effective biological control[85]. Collectively, these disruptions increasingly threaten crops in Balochistan-such as citrus and date palm-that have traditionally relied on natural enemies for sustainable pest regulation.

Research gaps and recommendations: Although, the ecological and economic consequences of climate change are increasingly recognized, research on insect populations in Balochistan remains limited, fragmented and largely reactive rather than proactive[30]. While studies have predominantly focused on crop production or broad climate trends, the underlying interactions between climatic variables and insect ecology have received comparatively little attention[86]. These knowledge gaps-including those related to sustainable pest management and biodiversity conservation-must be systematically identified and addressed to support effective climate adaptation in this highly vulnerable region[37].

Lack of long-term monitoring programs: A major research gap is the absence of long-term ecological surveys documenting insect population dynamics across the diverse agroclimatic zones of Balochistan[75]. Unlike regions with intensive entomological research, there are few standardized datasets tracking insect diversity, abundance, or seasonal phenology in response to climatic factors[87]. This lack of longitudinal data limits the development of predictive tools and early warning systems that could enable farmers and policymakers to anticipate pest outbreaks and pollinator declines[88].

Limited taxonomic and functional understanding of insect biodiversity: Most entomological studies in Balochistan have concentrated on economically important pest species, such as *Ommatissus lybicus* and *Bemisia tabaci*, whereas information on beneficial insects-including parasitoids, predators, decomposers and pollinators-remains scarce[89]. Furthermore, the functional roles of native insect species within local ecosystems are poorly understood. Assessing the resilience, adaptability and vulnerability of insect communities to climate change will require comprehensive taxonomic surveys and detailed ecological studies to facilitate more accurate evaluations and inform region-specific management strategies[90].

Inadequate integration of climate and insect data: Research in Balochistan has rarely combined climate information-such as atmospheric temperature trends, precipitation patterns and heatwave events-with entomological studies[91]. This disconnect limits the capacity to model insect population responses under projected warming and drought scenarios. Integrating Regional Climate Models (RCMs) with insect phenology and population dynamics could improve understanding of ecological tipping points, critical thresholds and adaptation windows[16].

Minimal research on biological control under climate stress: Although, biological control is promoted as an environmentally sustainable alternative to chemical pesticides, limited studies have assessed the performance of natural enemies under climate stress in the arid systems of Balochistan[92]. Climatic shifts in temperature and humidity can suppress parasitoid activity, disrupt predator-prey interactions and necessitate the development of adaptive biocontrol strategies[85].

Weak farmer awareness and extension services: A further critical gap exists in farmer awareness and capacity-building initiatives. Most farmers in Balochistan rely on traditional practices and lack access to real-time climate or pest forecasts[93]. Current extension programs addressing insect ecology, pollinator conservation and sustainable pesticide use are seldom integrated with climate-smart pest management strategies[94]. Participatory research approaches, community-based surveillance and localized agro-advisory services represent potential avenues for bridging this knowledge and practice gap.

RECOMMENDATIONS FOR FUTURE RESEARCH AND POLICY

Establish long-term insect biodiversity monitoring plots: A major limitation in Balochistan is the absence of systematic, long-term ecological records of insect populations. Most available information derives from short-term studies or farmer surveys, which are insufficient to capture gradual changes induced by climate variability[89]. Establishing permanent biodiversity monitoring plots across representative agroecological zones-such as the Makran coastal belt, Ziarat highlands, irrigated plains of Khuzdar and the desert areas of Chaghi-would provide baseline data on both pest and beneficial insect population dynamics. Comparable biodiversity observatories in India and Iran have proven invaluable for assessing insect community responses to rising temperatures and altered rainfall patterns[95]. Such monitoring would also equip policymakers with critical information to anticipate emerging pest threats and to implement conservation strategies for beneficial insects in Balochistan.

Promote interdisciplinary research: Climate change affects insect populations through multiple pathways, including alterations in plant physiology, predator-prey interactions and socio-economic factors[96]. Consequently, integrated research combining entomology, climatology, ecology and socioeconomics is essential to generate holistic insights. As highlighted by Al-Kindi et al.[97], linking climate modeling with insect life-history studies can improve forecasts of pest outbreaks and pollinator declines. Implementing such interdisciplinary approaches in Balochistan would facilitate the development of adaptation strategies that are both ecologically sustainable and socioeconomically viable[67].

Develop early warning systems and climate-informed IPM: Climate-resilient pest management relies on the deployment of early warning systems (EWS) that integrate real-time weather data, remote sensing and pest population modeling[98]. The FAO Locust Hub has demonstrated that satellite-based surveillance is effective for predicting desert locust swarm movements[99]. For Balochistan, region-specific tools should be developed for key pests, including Dubas bug, aphids and longhorn beetles. Integrating these tools into farmer advisory networks would enhance preparedness and reduce crop losses[100]. Additionally, the adoption of resistant crop cultivars, biological control agents and ecological habitat management should be incorporated into local agricultural policy through climate-smart Integrated Pest Management (IPM) frameworks[32].

Strengthen taxonomic training and documentation of native insects: Accurate identification of insect species remains a critical bottleneck for effective pest and pollinator management in Balochistan[91]. Many beneficial insects, including parasitoids, predators and wild pollinators, are poorly documented[5]. Enhancing pest diagnosis and ecological monitoring capacity requires investment in insect taxonomy and molecular tools such as DNA barcoding[101]. Training programs for entomologists and extension personnel should be prioritized, as misidentification frequently leads to ineffective pest control strategies. For example, the integration of molecular identification of coccinellid beetles in Punjab and Sindh has substantially improved the efficacy of biological control interventions, an approach that could be replicated in Balochistan[102].

Enhance research on climate-resilient biological control: Biological control agents, including parasitoids, predatory beetles and entomopathogenic fungi, constitute a sustainable component of pest management. However, their performance under fluctuating climatic conditions remains uncertain[103]. Evaluating these agents under controlled experiments simulating variable temperature and moisture conditions is essential to determine their functional stability. For instance, experimental trials with *Trichogramma* spp. in India and *Beauveria bassiana* in arid regions of Saudi Arabia demonstrated marked differences in efficacy under high-temperature conditions[104]. Similar studies in Balochistan would support the development of robust biological control programs targeting major pests such as the lesser date moth and Dubas bug.

Improve farmer education and policy engagement: Prior knowledge and awareness of climate risks are key determinants of successful pest management. Current extension programs in Balochistan inadequately address the intersections of climate change and pest dynamics[105]. This gap can be mitigated by strengthening farmer field schools, establishing online advisory platforms and promoting community-based pest monitoring initiatives[106]. At the policy level, incorporating pest risk assessments into climate adaptation frameworks and agricultural insurance schemes would enhance farmer resilience to pest outbreaks induced or exacerbated by changing climatic conditions.

CONCLUSION

Climate change continues to exert profound impacts on insect populations worldwide, with effects particularly pronounced in Balochistan due to its fragile arid landscape. In this region, chronic water scarcity, soil erosion and socioeconomic instability exacerbate the consequences of changing climatic patterns. Recent assessments indicate that extreme weather events—such as flash floods, prolonged droughts and unseasonal heatwaves-are already altering local agroecosystems. For instance, the 2022 flooding in Qila Saifullah resulted in the destruction of over 96% of crops, directly disrupting insect-plant interactions and destroying the habitats of pollinators and pest predators. Reports suggest that similar flooding events across Balochistan have had severe consequences for agriculture, livestock and rural infrastructure, underscoring the high vulnerability of local ecosystems. Beyond vegetation loss, these climatic extremes influence pest behavior, including movement patterns, disruption of diapause and alterations in generational cycles, thereby increasing the risk of outbreaks. Rising temperatures are shifting developmental thresholds, particularly for orchard pests. High-value fruit crops such as apples, cherries and grapes in Balochistan are experiencing stress due to reduced chilling periods and unpredictable rainfall, which not only diminishes fruit quality but also promotes pest proliferation, including aphids and fruit flies (INP-WealthPK, 2025). The resulting economic pressures compel farmers to manage pest populations during off-seasons, creating significant adaptive challenges. Climate variability also has broader implications for agriculture beyond pest dynamics. For example, anomalous weather in Gilgit-Baltistan was followed by an invasion of the armyworm (*Mythimna unipuncta*) in 2022, with populations persisting throughout the summer. This event highlights the importance of incorporating climate risk into pest monitoring and preparedness programs. Similar threats are likely in Balochistan, emphasizing the need for early warning systems to track invasive species under changing climatic conditions. Drought patterns in Balochistan have intensified in recent years. Meteorological and agricultural drought indices indicate an increase in both the frequency and severity of drought events between 2018 and 2022. Prolonged dry periods reduce populations of beneficial insects while favoring the proliferation of pest species adapted to arid conditions. On the mitigation front, emerging climate-responsive practices offer potential solutions. For example, in Uthal, agroecological studies have demonstrated that the combined use of botanical insecticides, such as neem and sticky traps effectively manages whiteflies and jassids in tomato production. These strategies are well-suited to low-input, arid agricultural systems, providing an environmentally sustainable approach to pest management under climate stress.

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