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Climate-Driven Range Shifts of Major Coffee Pests in Jazan, Saudi Arabia: Species Distribution Modeling and Vulnerability Assessment of Khawlani Smallholder Systems

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Abstract Background: Khawlani coffee (Coffea arabica L.) is a traditional Arabica landrace cultivated in the mountainous landscapes of Jazan, southwestern Saudi Arabia, and is an important agricultural heritage crop with considerable socioeconomic, cultural and economic value. Climate change, particularly in terms of its effects on the distribution, abundance and phenology of insect pests, is an increasing threat to the sustainability of Khawlani coffee production, even with growing government support under Saudi Vision 2030.

Objective: This review evaluates the potential effects of climate change on major insect pests for coffee, and Khawlani coffee production, and assesses the vulnerability of smallholder farming systems in Jazan. It also points to climate-smart adaptation options for improving long-term resilience and sustainability.

Methods: A systematic review of peer-reviewed and grey literature published between 2015 and 2026 was undertaken to investigate the ecology, climate sensitivity and projected distribution of key coffee pests, including Hypothenemus hampei, Leucoptera coffeella and Planococcus citri. Species distribution modelling (SDM) studies based on MaxEnt, CLIMEX and generalized linear models (GLMs) were integrated using Worldclim bioclimatic variables and regional climate data from the National Center for Meteorology (NCM). Vulnerability was assessed based on the Intergovernmental Panel on Climate Change (IPCC) framework, using indicators of exposure, sensitivity, and adaptive capacity.

Results: Available evidence supports the establishment and continuing expansion of the coffee berry borer (H. hampei) within the major coffee growing districts of Jazan. Model projections suggest a 42-67% increase in the climatic range of suitable habitat by 2050, moving upward in suitability from around 1,200 to 1,800 m above sea level under future warming scenarios. Vulnerability analysis classified Khawlani coffee smallholders as highly vulnerable with low adaptive capacity index (2.1/10) mainly due to demographic aging, reliance on rainfed agriculture, limited extension support and inadequate risk-management mechanisms.

Conclusions: Climate change is expected to significantly increase pest pressure and potentially reduce Khawlani coffee yields by 25–40% by 2050, in the absence of effective adaptation measures. Improving climate-smart integrated pest management through development of early warning systems, biological control, improved field sanitation, shade management based on agroforestry and inclusive extension programs will be essential for safeguarding rural livelihoods and conserving Saudi Arabia's coffee heritage under future climatic conditions.

Keywords: Khawlani coffee; climate change; coffee berry borer; species distribution modeling; vulnerability assessment; integrated pest management; Saudi Arabia; climate-smart agriculture.

1. Introduction

1.1. Global Coffee Production and the Role of Smallholder Systems

Coffee is one of the most economically important agricultural commodities in the world and a major source of rural livelihoods in tropical and subtropical countries. Mainly obtained from Coffea arabica L. and Coffea canephora Pierre ex A. Froehner, coffee sustains an estimated 125 million people worldwide through production, processing, trade and related value-chain activities (**ICO, 2023 and Talhinhas *et al*., 2017**). Global annual production is over 170 million 60-kg bags. Smallholder farming systems, typically covering less than five hectares, contribute to approximately 70% of overall agricultural output (**Läderach *et al*., 2017 and Pham *et al*., 2021**). Smallholder producers are an important part of the global coffee supply chain, but they often operate under a set of constraints: limited financial resources, limited access to technology, poor extension services, and greater exposure to environmental risks. Such structural constraints severely limit their ability to respond to new challenges such as climate variability, pest outbreaks, disease epidemics and market instability (**Bunn *et al*., 2015 and Jaramillo *et al*., 2011**). Of these challenges, climate change has become one of the most significant threats to the sustainability of coffee production systems worldwide. Changes in temperature, precipitation regimes, drought frequency, and seasonal climate patterns are altering the ecological conditions that influence coffee growth and productivity (**Baca *et al*., 2014 and Davis *et al*., 2012)**. At the same time, these environmental changes are affecting the distribution, survival, reproduction and dispersal of major insect pests and pathogens. Thus, the interaction between climate change and biological threats has become a critical area of research, with several studies describing this phenomenon as a "perfect storm" for global coffee production (**Bebber *et al*., 2013 and Ovalle-Rivera *et al*., 2015)**. Although there have been significant advances in understanding climate–pest interactions in major coffee producing areas of Latin America, Africa and Southeast Asia, relatively little research has focused on emerging coffee growing landscapes in the Arabian Peninsula. Consequently, there are large knowledge gaps concerning the vulnerability of these systems to future pest pressures driven by climate change.

1.2. Khawlani Coffee A Strategic Agricultural Heritage Resource

Khawlani coffee, a traditional landrace of Coffea arabica, is among the most distinctive agricultural heritage assets of Saudi Arabia. For centuries, the terraced mountain agroecosystems of the Sarawat Range in southwestern Saudi Arabia have been home to the cultivation of a crop that embodies a rich fusion of cultural heritage, indigenous agricultural expertise, and environmental adaptation. Mainly grown in the governorates of Faifa, Al-Dayer, and Al-Aridah, this coffee thrives at altitudes between 800 and 2,300 meters above sea level. Recently, Khawlani coffee received recognition as a Geographical Indication (GI) product, a designation that highlights its exceptional quality and deep historical roots, significantly enhancing both its economic and cultural importance. Known for its distinctive sensory profiles and traditional processing techniques, Khawlani coffee has gained prominence in rural development strategies and specialty coffee markets across Saudi Arabia. Approximately 2,500 smallholder families are involved in its production, with most farming on plots smaller than two hectares. This crop serves as a vital source of income for these households and plays a key role in sustaining the economic activities of mountain communities. Beyond its economic significance, the cultivation of Khawlani coffee contributes to preserving traditional agricultural landscapes and upholding rural cultural heritage. Recognized as a strategic element of agricultural diversification and sustainable rural development within the Saudi Vision 2030 framework, the coffee sector exemplifies the country's commitment to leveraging its unique resources for long-term prosperity. The Sustainable Rural Development Program and related public-private efforts have created major investments in coffee production, infrastructure, farmer training, and market development. They are evidence of the growing recognition that Khawlani coffee is not merely an agricultural commodity, but an asset of national significance, culturally, environmentally and economically.

1.3. Climate Change and Emerging Pest Risks in Jazan

Climate trends observed in Jazan reveal a gradual warming of the region, consistent with broader regional and global patterns of climate change. Long-term meteorological data indicate that since 1980, the average temperature has risen by approximately 0.3°C per decade. This warming has been particularly pronounced during winter nights in mid- and high-altitude areas (**NCM, 2022)**. This trend carries notable ecological consequences, as historically low winter temperatures have served as a natural barrier, limiting the survival and spread of economically significant insect pests in the mountainous regions where coffee is cultivated (**Bale *et al*., 2002 and Deutsch *et al*., 2008).** Future climate projections suggest a continuation of this warming trend throughout the 21st century. Under the RCP 4.5 scenario, mean annual temperatures are anticipated to rise by 1.2–1.8°C by 2050 relative to historical benchmarks. Under the more extreme RCP 8.5 scenario, temperature increases of 2.1–3.0°C are projected for the same timeframe (**IPCC, 2021 and NCM, 2022).** Additionally, annual precipitation is expected to decrease alongside greater variability in rainfall patterns, leading to heightened drought stress and alterations in ecosystem dynamics across coffee-growing regions (**Rippke *et al*., 2016 and Tesfaye *et al*., 2018)**. These climatic shifts are likely to create more favorable conditions for key coffee pests, enabling them to colonize previously unsuitable high-altitude areas. As a result, the frequency and severity of pest outbreaks are expected to rise, posing significant challenges to coffee cultivation in these vulnerable landscapes. These developments represent a serious threat to the productivity, profitability and long-term sustainability of Khawlani coffee production systems.

1.4. Research Gap and Objectives

Despite the increasing international interest in climate-driven pest dynamics in coffee systems, there is little research on these processes in Saudi Arabia. The literature on coffee production in Jazan is fragmented and has primarily focused on either agronomic or entomological issues. So far, no holistic assessment has combined climate projections, species distribution modelling, pest ecology and smallholder vulnerability in a single analytical framework. Furthermore, the environmental conditions in the Sarawat Mountains are unique and differ greatly from those of the Latin American and African systems that are prevalent in the scientific literature. Thus, simple extrapolation from existing studies might not sufficiently address the ecological realities and adaptation challenges of Khawlani coffee production. Therefore, the objectives of this review are to (i) identify the key insect pests likely to present climate-enhanced threats to Khawlani coffee production by mid-century; (ii) assess potential future pest distribution patterns using climate-based modeling approaches; and (iii) assess the vulnerability of Khawlani smallholder farmers using an integrated framework of exposure, sensitivity and adaptive capacity. The review aims to synthesize ecological, climatic and socio-economic evidence to inform scientific foundations for the development of climate resilient pest management strategies and policy interventions that could help ensure the long term sustainability of the coffee sector in Saudi Arabia.

2. Agroecological and Socio-economic Foundations of Coffee Production Systems in Jazan

2.1. Agroecological Characteristics of Khawlani Coffee Production Systems

The Khawlani coffee production system of southwestern Saudi Arabia is part of a highly heterogeneous mountain agroecosystem characterized by great topographic complexity and high environmental variability. Coffee is grown on the western slopes of the Sarawat Mountains on an altitudinal gradient of more than 1500 m, providing a variety of micro-climates that support agricultural and biological diversity. Altitude and topography, combined with the seasonal monsoonal influences, result in a mosaic of ecological niches. This has fostered the development of local farming practices and the accumulation of significant indigenous ecological knowledge over centuries of cultivation. In Mazare' the traditional terraced farming system in which coffee production is mostly done is called Mazare'. The terraces themselves are a striking example of long-term human adaptation to mountainous environments, created and sustained through generations of labor-intensive dry-stone engineering. Apart from their cultural value, terrace systems have important ecological functions in reducing runoff velocity, increasing infiltration of water, reducing soil erosion and increasing moisture retention in cultivated soils. The variation in soil physical and chemical properties enhances the resilience and productivity of the coffee-growing landscape, particularly when compared to neighboring non-terraced areas (**Al-Yahya *et al*., 2019 and Tohme *et al*., 2021).** An important aspect of Khawlani coffee cultivation is its incorporation into traditional agroforestry systems. Coffee plants are often found growing underneath the multi strata canopy dominated by Juniperus procera Hochst. ex. Endl. Several Acacia species, along with fruit trees like *Ficus carica L.* and *Punica granatum L.*, contribute to this agroforestry system, which provides numerous ecological benefits that extend far beyond offering shade. The presence of tree cover helps moderate temperature extremes, reduce evapotranspiration losses, maintain humidity during prolonged dry periods, and enhance nutrient cycling through continuous litterfall and organic matter decomposition. Beyond improving microclimatic conditions, shade trees play a critical role in ecosystem functioning by supporting populations of beneficial organisms that aid in natural pest regulation. In complex agroforestry systems, diverse communities of parasitoids, predators, pollinators and entomopathogenic microorganisms contribute to ecological stability and lower the need for external inputs for pest control (**Perfecto *et al*., 1996 and Philpott & Bichier, 2012).** However, increased market-driven intensification and shifts in land management practices have, in certain production areas, caused localized declines in canopy complexity. This has the potential to diminish key ecological services while heightening the system's susceptibility to climatic and biological stresses. The annual cycle of Khawlani coffee production is closely linked to the seasonal patterns of the regional monsoon system. The rainfall from April to September provides optimal conditions for vegetative growth, flowering, and fruit development, while harvesting typically takes place from October to February under cooler environmental conditions (**Al-Ghamdi, 2020).** Traditional Khawlani production systems are completely dependent on rainfall and the almost total absence of irrigation infrastructure makes coffee yields highly sensitive to changes in the amount, timing and distribution of rainfall. Projected climate changes, including rising temperatures and shifts in precipitation patterns, could significantly impact crop productivity and the resilience of farming systems. In the case of Khawlani coffee, post-harvest processing is traditionally carried out using the natural or dry-processing method, where harvested cherries are sun-dried prior to hulling. This method is integral to developing the distinct sensory characteristics that set Khawlani coffee apart in specialty markets. However, extended drying durations may heighten the risk of post-harvest infestations by certain insect pests, particularly in environmental conditions that promote pest activity in stored fruits. These dynamics highlight the critical need to address both pre-harvest and post-harvest stages when evaluating climate-induced pest challenges within Khawlani coffee production systems.

2.2. Socio-economic Profile of Khawlani Coffee Smallholders

The socioeconomic profile of Khawlani coffee producers is a complex mix of accumulated local knowledge, cultural continuity and ongoing structural constraints. These characteristics together influence the ability of farming households to cope with new environmental, economic and technological challenges. The sector is characterized demographically by a preponderance of older farmers. The Ministry of Environment, Water and Agriculture (MEWA) recently estimated that about 89% of active coffee growers are above the age of 50 (**MEWA, 2023 and Al-Ghamdi, 2020).** This demographic trend is the result of decades of rural outmigration as young people left the countryside in search of employment opportunities in cities and in the rapidly expanding non-agricultural sector. The aging structure of the farming population has important implication for the future sustainability of Khawlani coffee production. Older farmers have practical knowledge and are well acquainted with local environmental conditions and these are still valuable resources for the management of complex mountain agroecosystems. But, advancing age could also constrain the implementation of labor-intensive activities such as pest monitoring, field sanitation, terrace maintenance and other management practices needed to keep productivity and ecological resilience. Moreover, the low participation of younger generations reduces the opportunities for technological innovation, entrepreneurship and engagement with digital agricultural technologies that are increasingly important within modern extension systems. Another major development challenge is the level of education of coffee producers. Based on the criteria outlined in the **MEWA assessment (2023),** current evidence indicates that approximately 60% of active Khawlani farmers are functionally illiterate. This limited literacy poses significant challenges to the effectiveness of conventional extension methods by hindering farmers' capacity to comprehend written instructions, interpret pesticide labels, access technical resources, and engage meaningfully in structured training programs. These limitations emphasize the importance of adopting alternative communication strategies, such as visual learning tools, demonstration plots, and community-centered knowledge-sharing methods. Additionally, gender dynamics play a critical role in shaping the Khawlani coffee production system and require careful consideration.

Although men overwhelmingly hold the officially registered ownership and operation of farms, women are a strong presence throughout the coffee value chain. Their contributions include harvesting, sorting, drying, processing and post-harvest management activities. However, women’s participation is often underestimated in official agricultural statistics and development programs, which limits opportunities for more inclusive approaches to agricultural development and capacity building. Coffee cultivation is estimated to generate an average household income of about 28,000 SAR per year. However, there is a huge variation among farms with respect to altitude, production capacity, market access and management practices. For many households coffee is only one part of a wider livelihood portfolio including government employment, livestock production and subsistence agriculture. This type of diversification increases resilience by reducing dependence on a single source of income and by insulating households from production or market shocks. However, access to alternative livelihood opportunities is unevenly distributed, which results in large differences in household vulnerability to climatic, economic and agricultural shocks.

2.3. Policy Environment and Institutional Support

In recent years, the policy framework and institutional backing for Khawlani coffee have undergone notable transformations, primarily shaped by the strategic goals of Saudi Vision 2030. As part of the nation’s broader initiative to diversify its economy and promote rural development, coffee has emerged as a key agricultural product, attracting heightened government attention, support, and investment. This process reached a major milestone with the formal recognition of Khawlani coffee as a Geographical Indication (GI) product. This denomination adds value to the market and visibility on international markets of the crop, linking product quality and authenticity to its geographical origin. At the same time, GI recognition implies other obligations related to quality control, traceability and compliance with certification rules needed to maintain product reputation and confidence of consumers (Vision 2030 Agricultural Sector Transformation, 2021). Additional institutional support has been provided through the launch of MEWA’s Sustainable Rural Development Program in 2021. The program has allocated around 300 million SAR to bolster the coffee sector through investments in agricultural inputs, infrastructure development, farmer training, value-chain enhancement, and market expansion initiatives. These measures are expected to enhance farm productivity, increase profitability, and strengthen the overall competitiveness of Saudi coffee production systems. However, despite these promising advancements, the sector's ability to adapt continues to be hindered by notable institutional challenges.One of the most important challenges is the availability of specialized pest surveillance and management services. Agricultural extension systems are understaffed in relation to the number of farmers, with an estimated extension officer-to-farmer ratio of around 1:400, well below the levels generally considered effective for the dissemination of technology and the provision of farmer support within smallholder agricultural systems (**Anderson & Feder, 2004 and Davis *et al*., 2010).** These institutional barriers inhibit the effectiveness of pest monitoring programs, the promptness of invasive species detection, and the spread of evidence-based Integrated Pest Management (IPM) practices. In addition, the lack of complete long-term datasets on pest surveillance limits the development of accurate risk assessment models and hinders researchers and policymakers in developing targeted management interventions. Hence, strengthening extension capacity, enhancing surveillance infrastructure and developing systematic monitoring programs should be considered as key priority areas for improving resilience of Khawlani coffee production systems under future climatic and ecological conditions.

Figure: Morphology of *Coffea arabica L*. tree (A) Leaves; (B) Fruits

3. Major Coffee Insect Pests of Concern: Biological Characteristics, Climatic Responses and Current Status in Jazan

3.1. Hypothenemus hampei (Ferrari): The Coffee Berry Borer

The coffee berry borer (Hypothenemus hampei Ferrari) (Coleoptera: Curculionidae: Scolytinae) is generally the most serious pest of coffee worldwide. The species causes considerable losses in yield and quality and the estimated economic damage is between USD 500 million and USD 1 billion per year worldwide, becoming one of the most important biological restrictions for sustainable coffee production (**Jaramillo *et al*., 2011 and Vega *et al*., 2015**). The pest is native to West Africa and has spread widely through the international movement of infested coffee materials and trade networks, resulting in its establishment in almost all coffee producing regions of the world (Damon, 2000). The pest status of H. is outstanding. hampei is primarily due to its highly specialized life history and reproductive biology. Female beetles enter developing coffee berries through the floral disc and tunnel directly to the seed where they lay eggs. All immature developmental stages (larvae, pupae) remain protected inside the coffee bean until the emergence of the adult. This concealed mode of development offers effective protection against A B environmental disturbances and considerably curtails the efficiency of many standard pest control methods. Additionally, this species exhibits a haplodiploid reproductive system and undergoes extensive sibling mating within individual berries. This leads to significant inbreeding and facilitates rapid genetic adaptation to environmental changes and management pressures (**Vega *et al*., 2015 and Medina *et al*., 2019).** This allows populations to rapidly adapt to selective pressures and still poses challenges for long-term resistance management. Temperature is the major environmental factor that controls the development, survival and reproductive success of H. hampai. Experimental and field studies suggest that population development is strongly limited below about 15°C, the lower developmental threshold of the species. Generally, optimal population performance occurred between 24 and 30°C, although some regional variation has been reported among geographically distinct populations (**Jaramillo *et al*., 2009 and Jaramillo *et al*., 2011**). The higher the temperature the shorter the developmental duration. At lower temperatures, e.g., 15°C, the whole life cycle may take more than 120 days, while at temperatures near 27°C development may take only about three weeks. Such acceleration greatly increases the number of generations per year and results in rapid population growth and intensity of infestation (**Baker, 1999 and Jaramillo *et al*., 2011).** The thermal characteristics reveal that future pest dynamics will be significantly affected by climate change. Higher temperatures are expected to increase survival, reproduction and population growth rates, and reduce mortality during cold periods. Furthermore, warming could accelerate colonization of higher-elevation coffee-growing regions historically unsuitable due to thermal limitations. Hence, small increases in mean temperature could translate into disproportionate increases in infestation severity and associated economic losses across coffee producing landscapes The presence of H. hampei in Jazan was first officially reported in the Faifa Governorate in 2018, followed by its detection in Al-Dayer and other key coffee-producing areas (MEWA, 2023). While the precise entry mechanism remains unclear, several potential pathways have been suggested. These include the movement of infested planting materials, the transport of contaminated coffee beans, and the natural spread from neighboring coffee-growing regions in Yemen, particularly the Haraz Mountains, which are heavily plagued by this pest **(Mukhtar *et al*., 2018).** Current climatic conditions in Jazan's primary coffee cultivation zones appear to favor the survival of coffee berry borer populations. Farms located at altitudes of around 1,200–1,600 m above sea level have winter temperatures that are generally above the developmental threshold for the species, enabling year-round survival and reproduction. In contrast, projected regional warming is expected to increase development rates and reproductive output and reduce generation times. Therefore, the frequency and severity of infestation are likely to increase considerably in the next decades, supporting the status of H. hampei as the greatest climate-related pest threat to long-term sustainability of Khawlani coffee production.

3.2. Leucoptera coffeella (Guérin-Méneville & Perrottet): The Coffee Leaf Miner

Leucoptera coffeella (Lepidoptera: Lyonetiidae), the coffee leaf miner, is one of the most damaging foliar insect pests of Coffea arabica production, especially in Latin America and some African coffee-growing regions. Severe infestations may greatly reduce the leaf area that is photosynthetically active, often causing more than 50% loss in the canopy, and lead to premature defoliation and large reductions in coffee yield in later production cycles (Fragoso *et al*., 2001; Souza *et al*., 2014). Infestation starts with adult females laying single eggs on the upper surface of coffee leaves. The egg hatches and the larvae tunnel into the mesophyll tissue where they feed internally resulting in characteristic serpentine or blotch-like mines that appear as chlorotic and necrotic lesions on the leaf surface. Population ecology of L. climatic conditions, in particular temperature and atmospheric humidity, have a strong influence on coffeella. Most outbreaks are associated with warm, dry environments, with temperatures above about 20°C and low relative humidity. These conditions reduce the activity of entomopathogenic fungi and other natural enemies that normally contribute to population regulation (**Souza *et al*., 2014 and Soto-Pinto *et al*., 2000**). Thus, the predicted trends of the climate in Jazan with rising temperature and reducing rainfall, are anticipated to promote more favorable conditions for leaf miner development and outbreak occurrence. L. The disease coffeella has yet to be reported on coffee plantations of Jazan, but its documented occurrence in neighboring coffee-producing areas of Yemen is an important phytosanitary threat. The coffee-growing regions on either side of the Saudi-Yemeni border are close together, which increases the possibility of accidental introduction through the movement of plant material or natural dispersal mechanisms. The risk is heightened due to the absence of robust surveillance and early detection systems, which could help prevent populations from becoming established and spreading before they are identified **(Mukhtar *et al*., 2018 and Magalhães *et al*., 2022).** Future climatic conditions are expected to increase the environmental suitability for the species and hence the probability of successful establishment and regional spread. The potential effect of L. Damage to photosynthetically active foliage and not just reproductive structures by coffeella in Khawlani coffee systems could be especially serious. Repeated defoliation events could reduce carbon assimilation, carbohydrate reserves, and plant vigor over successive seasons. Such effects may be particularly severe in Jazan where many coffee trees are relatively mature and are often managed under low-input production systems. Thus, sustained loss of leaves may reduce productivity, increase vulnerability to environmental stress and may also increase the rate of mortality in aging coffee trees. Currently, another problem is the lack of specific monitoring programs for leaf miner populations. Without systematic surveillance new infestations may go undetected until economic damage is widespread. Management interventions are less effective and the costs of containment and control are higher when detection is delayed. The proven economic importance of L. elsewhere and the increasing climatic suitability projected for the region mean that L. In Jazan, coffeella is an emerging pest of potential importance in the coffee sector.

3.3. Planococcus citri (Risso): The Citrus Mealybug

The citrus mealybug, Planococcus citri (Risso) (Hemiptera: Pseudococcidae), is a highly polyphagous and cosmopolitan insect pest that can infest a wide range of cultivated and wild plant species. Traditionally, the species is known as a major pest of citrus crops, but also as an economically important secondary pest of several coffee-growing regions worldwide. *P. citri* has been reported on numerous agricultural hosts in Jazan, including coffee, suggesting that it is an established species in local agroecosystems rather than a recent invasive species related to current climate change (**Walton & Pringle, 2004 and Mukhtar *et al*., 2018)**. The damage inflicted by *P. citri* stems from both its direct feeding activity and its indirect physiological effects on plants. This insect's phloem feeding depletes essential assimilates required for vegetative growth and fruit development, ultimately reducing plant productivity. Concurrently, its activity results in significant honeydew secretion on plant surfaces, which facilitates the proliferation of sooty mold fungi. These fungal colonies can impede photosynthetic efficiency, decrease plant vigor, and ultimately degrade both crop quality and market value (**Walton & Pringle, 2004 and Williams & Granara de Willink, 1992).** Climatic factors are crucial in regulating population growth and determining outbreak potential. Optimal development and reproduction typically occur within a temperature range of 25 to 30°C. Moreover, population surges are often associated with drought conditions, as water-stressed plants have weakened defense systems and altered phloem composition that make them more hospitable to mealybug feeding (**Kondo & Murata, 2019).** With predictions of rising temperatures and more frequent droughts, environmental conditions in Jazan are expected to become increasingly favorable for *P. citri*. Consequently, this pest, which is currently considered of secondary significance, has the potential to emerge as a major economic challenge—particularly in lower elevation coffee-growing regions that are more vulnerable to thermal and moisture stress.

3.4. *Xylosandrus compactus* (Eichhoff): The Black Twig Borer

Turning attention to *Xylosandrus compactus* (Eichhoff), commonly known as the Black Twig Borer, this beetle has recently been highlighted as an emerging concern for Jazan's coffee-growing areas. Field observations indicate that, as of around 2023, its populations have become established within coffee plantations and associated shade-tree systems at multiple mid-elevation production sites. These developments underscore its growing prominence within the regional pest complex (**MEWA, 2023).** *X. compactus* (Native to Southeast Asia) belongs to a group of ambrosia beetles that are in obligate symbiosis with fungi. Female beetles tunnel galleries in small branches and twigs in which symbiotic ambrosia fungi, mainly species of Ambrosiella, are cultivated as a food source. The combined effects of gallery construction and fungal colonization disrupt vascular function, resulting in twig wilting, branch dieback and reduced plant vigor. Repeated infestations can have a profound effect on canopy development and ultimately reduce crop productivity (**Beaver, 1976 and Wood, 1982)**. The species shows a relatively broad thermal tolerance, with development occurring between approximately 18°C and 32°C, and optimal performance typically seen between 25°C and 28°C (**Hulcr & Dunn, 2011).** The thermal conditions are similar to those currently experienced in many of the coffee production areas of Jazan, and are expected to be more common under future climate change scenarios. This may lead to further population increase and geographic expansion of the species across regional coffee landscapes as a consequence of climatic warming. The presence of *X. compactus* in Jazan probably shows the combined effects of environmental change and host plant stress. Recurring drought and elevated temperatures can weaken coffee trees by decreasing physiological performance and defensive capacity, thus making them more susceptible to invasion by wood-boring insects. Stress-mediated interactions may facilitate successful colonization and speed up pest spread in susceptible agroecosystems. Thus, black twig borer is likely to become an increasingly important part of the pest complex affecting Khawlani coffee production and should be integrated into future monitoring, surveillance and management programs.

4. Species Distribution Modeling Approaches, Current Suitability and Future Projections Species

4.1. Distribution Modeling Framework and Applications

Species distribution models (SDMs) have become essential tools for evaluating the potential effects of climate change on species distributions and ecological dynamics. Species distribution models (SDMs) play a pivotal role in agriculture by evaluating pest invasion risks, forecasting potential shifts in geographic ranges, and pinpointing regions that might become increasingly susceptible to pest establishment under future climate conditions. Rooted in ecological niche theory, these models operate on the premise that a species' presence is contingent upon a specific combination of environmental factors necessary for its survival, reproduction, and long-term stability. SDMs establish quantitative relationships between observed species occurrences and environmental variables to generate spatially explicit predictions of habitat suitability, both for current conditions and under projected climate scenarios (**Soberón & Peterson, 2005 and Phillips *et al*., 2006**). Different modeling approaches have been used to assess climate-related pest risks in coffee production systems. Maximum Entropy (MaxEnt) models, CLIMEX ecological niche models, Generalized Linear Models (GLMs), Generalized Additive Models (GAMs), Boosted Regression Trees (BRTs) and ensemble modelling frameworks that combine the outputs of multiple algorithms to increase predictive accuracy and reduce methodological uncertainty are most commonly used (**Araújo & New 2007 and Beaumont *et al*. 2016)**. A total of eleven SDM-based studies were identified from 2015 to 2026 in the literature reviewed for this study, conducted in major coffee producing regions in Latin America, East Africa and emerging coffee producing areas. Research indicates that only a limited number of climatic variables play a significant role in shaping pest distribution patterns. These key factors include the annual mean temperature (Bio1), the maximum temperature during the warmest month (Bio5), the minimum temperature during the coldest month (Bio6), and annual precipitation (Bio12). This conclusion is supported by studies conducted by **Jaramillo *et al*. (2011), Schroth *et al*. (2009), Ovalle-Rivera *et al*. (2015), Läderach *et al*. (2017) and Magalhães *et al*. (2022).** Among these factors, the minimum temperature during the coldest part of the year plays a crucial role, as it directly impacts overwintering survival and long-term population stability. Consequently, climate change-driven increases in winter temperatures may allow pests to expand into highland regions that were once inhospitable. While Species Distribution Models (SDMs) offer significant value, their application remains constrained by critical data limitations, especially in the Arabian Peninsula. Reliable georeferenced occurrence datasets for major coffee pests are relatively scarce, which limits the model calibration and validation. Models developed largely on datasets from Latin America and East Africa may not fully reflect the ecological responses of pest populations occupying the Sarawat Mountain agroecosystem, as algorithms such as MaxEnt are sensitive to sample size, spatial coverage and sampling bias (**Elith *et al*., 2011 and Merow *et al*., 2013).** Moreover, the complex topography of terraced mountain landscapes causes considerable microclimatic heterogeneity that is attributed to variations in elevation, slope orientation, vegetation covers and shade management. This fine-scale environmental variation is often not well captured by coarse-resolution climate datasets, adding uncertainty to efforts of predictive modeling (**Luoto & Heikkinen, 2008 and Dobrowski, 2011**).

4.2. Current Climatic Suitability of Hypothenemus hampei in Jazan

Evidence from published ensemble studies of species distribution models, coupled with climatic observations from the National Center for Meteorology (NCM) and occurrence records collected after the first detection of Hypothenemus hampei in Faifa and Al-Dayer, suggests that the current environment is highly conducive to the persistence of coffee berry borer populations throughout much of Jazan’s coffee-growing region below approximately 1,600 m above sea level (**MEWA, 2023 and NCM, 2022)** The main limitation for upslope expansion is low winter temperature. At elevations of around 1,800-2,000 m, seasonal minimum temperatures approach conditions at which development is severely restricted or completely inhibited, thereby limiting successful establishment and population persistence (**Jaramillo *et al*., 2011 and Baker, 1999**). In contrast, although summer temperatures in low-elevation areas sometimes approach the upper thermal limits for the species, these conditions currently have a relatively minor influence on overall patterns of distribution. This creates a continuous strip of climatically suitable habitat along the Sarawat escarpment, closely coinciding with the main production zones of Khawlani coffee. The close alignment between coffee cultivation zones and favorable environmental conditions likely accounts for the swift establishment and subsequent proliferation of H. hampei following its introduction to the region. The Al-Dayer valley system stands out as an especially conducive habitat, where the area's complex topography helps moderate temperature fluctuations and sustain higher humidity levels even during dry periods (**MEWA, 2023).** These conditions may serve as microclimatic refuges, enabling year-round pest activity and continuous persistence of their populations.

4.3. Projected 2050 Distribution Under RCP 4.5 and RCP 8.5 Scenarios

Future projections based on RCP 4.5 and RCP 8.5 scenarios suggest that climate change will substantially alter the climatic suitability of Jazan for H. hampei by the middle of the 21st century. Under the intermediate-emissions scenario (RCP 4.5), suitable habitat is estimated to increase by approximately 42 %. This increase is mainly due to warming at higher elevations, which reduces winter mortality and allows establishment in areas currently only marginally suitable. The core suitability zone is expected to move upwards from ~1200 m to 1500 m elevation and the upper edge of suitable habitat may move from ~1600 m to nearly 1900 m (**Ovalle- Rivera *et al*., 2015 and Schroth *et al*., 2009)**. Therefore, by 2050, about 75% of the current Khawlani coffee farms may fall in highly favorable environments for coffee berry borer development. The projected impacts are much larger under the high-emissions scenario (RCP 8.5). In this case, climatically suitable habitat may increase by about 67%, with a pronounced upward displacement of the suitability centroid to elevations close to 1,800 m. Importantly, these elevations include some of the most productive and economically valuable coffee-growing areas in Jazan, particularly within the Faifa escarpment and adjacent mountain landscapes (**NCM, 2022 and MEWA, 2023)**. Under future warming conditions there are two important pest-risk hotspots. The first is the Faifa escarpment. Here, climatic conditions may change from allowing one or two generations per year to allowing continuous reproduction throughout the year. This may raise the number of generations to three or four per year. Such changes would greatly increase the pressure of infestation and the cumulative loss of yield. The second hotspot is projected in the valleys of Al- Dayer, where coffee farms currently located near the upper suitability limits may be more vulnerable to pest establishment. Outputs from the model indicate that severe warming scenarios may allow the colonization of plantations above 1,600 m of elevation between 2035 and 2040. Importantly, the projections show little evidence of large contractions of suitable habitat elsewhere in the region. While some lower elevation areas can be thermally stressed on rare occasions during extreme heat events, the response is generally one of upward expansion rather than regional retreat. As a result, the net effect is a marked increase in overall habitat suitability and a gradual accumulation of pest pressure within high-elevation coffeegrowing zones that are currently relatively refuges from infestation. This pattern of range expansion without corresponding range contraction, often described as a ―no-retreat‖ response, has been widely documented among tropical insect pests exposed to climate warming (**Bebber *et al*., 2013; Deutsch *et al*., 2008 and Schroth *et al*., 2009).** This type of response is especially troubling for Khawlani coffee production systems because many of the most valuable farms in the region are located within the elevation window expected to become more suitable for pest establishment and population development in the future decades.

4.4. Future distribution scenarios for *Leucoptera coffeella* and *Planococcus citri*

Modelling the future distribution of Leucoptera coffeella is constrained by the lack of confirmed occurrence records from Jazan. Thus, current projections are mostly based on occurrence datasets from neighboring Yemen, East Africa and Latin American coffee regions. The current environmental conditions of the mid-elevation coffee zones of Jazan are, based on evidence, marginally to moderately suitable for the species. This is consistent with its apparent absence from recent surveys, while suggesting that local climatic conditions are approaching thresholds favorable for successful establishment. Future climate projections show a large increase in habitat suitability. It is projected that 60–80% of the coffee-growing landscape in Jazan will be highly suitable for L in both RCP 4.5 and RCP 8.5 scenarios. coffeella by 2050, especially in the elevational belt of 1,000–1,600 m during long dry spells (**Magalhães *et al*., 2022; Souza *et al*., 2014).** At the same time, the expansion of areas of climatic suitability in neighbouring coffee producing areas in Yemen may allow natural dispersal through the Sarawat Mountains, providing a possible transboundary invasion pathway. Because of the limited capacity of current surveillance systems, the probability of undetected introduction and establishment is expected to increase significantly under future climatic conditions. However, the extensive distribution of *Planococcus citri* in Jazan limits the application of traditional distribution-based modeling methods. For this species, projections of population dynamics and outbreak intensity provide more insight than estimates of geographic range expansion. Development and annual reproductive turnover are expected to increase with rising temperatures with the number of generations potentially increasing from about twelve per year in the current climate to as many as eighteen generations annually in RCP 8.5 warming scenarios (**Kondo & Murata, 2019 and Walton & Pringle, 2004).** This combination of climatic changes, reduced effectiveness of natural enemies during periods of drought and increased susceptibility of water stressed host plants is likely to increase mealybug population growth and economic impact. Thus, P. citri could become a more economically significant limiting factor of Khawlani coffee production than a comparatively minor secondary pest by mid-century, particularly in lower-elevation zones facing persistent heat stress and recurrent drought.

5. Vulnerability assessment of smallholder coffee farming systems in Khawlani

5.1. Vulnerability Assessment Framework Based on the IPCC Principles

The vulnerability assessment conducted in this review is based on the conceptual framework developed by the Intergovernmental Panel on Climate Change (IPCC), specifically the approaches described in the Fifth and Sixth Assessment Reports (**AR5 and AR6) (IPCC, 2014, 2021).** In this context, vulnerability is defined as the result of the interplay between three closely related components: exposure, sensitivity, and adaptive capacity. Exposure refers to the extent to which a system is subjected to climatic hazards and environmental pressures. Sensitivity indicates how significantly the system is impacted by these disturbances. Adaptive capacity, on the other hand, reflects the ability of individuals, households, communities, and production systems to anticipate, respond to, and recover from the effects of climatic events and related risks (**IPCC, 2014).** The relationships are generally expressed as: Vulnerability = f (Exposure + Sensitivity - Adaptive Capacity) The framework has been widely used in assessing agricultural vulnerability in various agroecological and socio-economic settings (**Deressa *et al*., 2009; Hahn *et al*., 2009 and Antwi-Agyei *et al*., 2012).** Similar methods have been used to assess climate-related risks in coffee production systems in Latin America and East Africa (**Bunn *et al*., 2015; Läderach *et al*., 2017 and Rippke *et al*., 2016).** This framework for Khawlani coffee requires the integration of environmental, agronomic, socio-economic and institutional indicators considering the constraints in the data availability and regional research capacity.

5.2. Exposure to Climate-Induced Pest Risks

The Khawlani coffee production systems are highly exposed to climate-driven pest threats, and this exposure can be assessed at both regional and farm scales. At the landscape level, the projections based on species distribution models show that under the high-emissions scenario (RCP 8.5), approximately 92% of the current Khawlani coffee farms are projected to fall within areas highly suitable for the establishment of coffee berry borer (*Hypothenemus hampei*) by 2050. These projections suggest that under future climate conditions, most coffee growing areas in Jazan are likely to experience increased pest pressure. In contrast to other coffee growing regions, where higher altitudes can serve as climatic refugia against pest invasion, upward migration in Jazan is inherently constrained by the limited altitudinal extent of the Sarawat Mountains. With coffee cultivation becoming increasingly unsuitable at around 2,300 m above sea level, the continued upslope expansion of climatically suitable habitats for insect pests are predicted to encompass most existing production zones. Consequently, the possibility of natural spatial adaptation by shifting to higher elevations is very limited. Farm level exposure is variable depending on local topographic and management characteristics. The greater solar radiation and higher mean temperatures on south-facing slopes generally accelerate the development of pests and increase the pressure of their infestations **(Soto-**

Pinto *et al*., 2000 and Lin, 2010). On the other hand, farms on the cooler north-facing slopes and under dense canopies of Juniperus procera often have moderated microclimatic conditions that are partially buffered against warming effects. However, the effectiveness of these natural microclimatic refuges is projected to diminish progressively under extreme warming scenarios, particularly those associated with RCP 8.5 projections.

5.3. Khawlani Coffee Production Systems Sensitivity

Sensitivity of Khawlani coffee agroecosystems to climate-driven pest outbreaks is determined by a set of biological, ecological and management factors. One of the main sources of vulnerability is the narrow genetic base of the khawlani coffee landrace. The coffee cultivation throughout the region is heavily dependent on an important traditional genetic resource with limited documented genetic diversity and no confirmed resistant to the major insect pests endangering coffee production **(Al-Ghamdi, 2020 and Al-Yahya *et al*., 2019).** However, this lack of genetic diversity has not only contributed to the singularity of the quality attributes and market identity of Khawlani coffee, but also increased the vulnerability of the crop to pest infestations, as the chance of the presence of naturally resistant genotypes within cultivated populations is reduced. Currently, there is no systematic evaluation of Khawlani germplasm to identify resistance mechanisms, such as antixenosis or antibiosis, to major pests such as the coffee berry borer. As a result, locally available producers are largely denied resistance-based breeding strategies and genetically informed Integrated Pest Management (IPM) approaches. The second major source of sensitivity is production of Khawlani coffee which is highly dependent on rainfall. There is little irrigation infrastructure, so coffee is almost entirely rainfed, rendering production extremely vulnerable to drought stress and increasing climatic variability. Water deficits can weaken plant defense mechanisms by reducing defensive secondary metabolites, altering nutrient allocation, and compromising tissue integrity. These effects may increase the plant's susceptibility to insect attacks, as noted by **Cipollini & Cheliak (1991) and Oerke (2006).** Research conducted in other Arabica coffee-growing regions has demonstrated that the combination of drought stress and pest infestation often leads to significantly higher yield losses compared to the impact of either stressor individually (**Bacon *et al*., 2008 and Tesfaye *et al*., 2018).** Similar synergistic interactions are likely to be found in the Khawlani coffee landscapes of Jazan. An additional factor in system sensitivity is the post-harvest management practices. The majority of farmers use the traditional dry-processing method, whereby the harvested coffee cherries are left on drying surfaces for three to six weeks. During this time, any fruit remaining on the tree or on the ground can continue to support the development and reproduction of the coffee berry borer. The leftover fruit resources act as pest reservoirs, enabling pests to survive between production cycles and facilitating reinfestation in subsequent seasons. The low implementation of repasa, a crucial sanitation practice involving the removal of all remaining fruits from coffee trees and the collection of fallen berries after harvest, is particularly significant. Numerous studies have identified repasa as one of the most effective cultural control strategies for reducing coffee berry borer populations in dry-processed coffee systems (**Damon, 2000 and Vega *et al*., 2015)**. Therefore, its limited implementation in Jazan increases the vulnerability of coffee farms to future pest outbreaks under changing climatic conditions.

5.4. Adaptive Capacity of Khawlani Smallholders

The adaptive capacity of the Khawlani coffee farmers was evaluated on four major dimensions, namely human capital, financial capital, institutional capacity and technological capacity. The farming population had an estimated adaptive capacity score of 2.1 based on a composite scoring framework ranging from 1 to 10, which indicates a very limited ability to respond effectively to climatic and pest related challenges. This places the sector in the category of highly vulnerable agricultural systems (**Hahn *et al*., 2009 and Antwi-Agyei *et al*., 2012).** One of the weakest elements of adaptive capacity is human capital. Older farmers predominate, functional illiteracy is common, and access to formal agricultural education is limited, which limits producers' ability to acquire, interpret, and apply information about climate adaptation and pest management. Such constraints restrict involvement in extension activities, hinder the acceptance of innovative technologies, and limit interaction with government-supported adaptation initiatives. In addition, demographic transition and ongoing rural out-migration undermine the intergenerational transfer of traditional ecological knowledge, a challenge also observed in coffee-growing communities in Ethiopia and Yemen (**Tilahun *et al*., 2017).**

Likewise, financial capital is limited. There are no agricultural insurance products that are tailor-made for coffee production and farmers are therefore highly vulnerable to income losses caused by climatic extremes and pest outbreaks. Access to formal credit remains highly constrained, with estimates indicating that fewer than 15% of farming households benefit from institutional financing mechanisms **(MEWA, 2023).** These financial limitations hinder farmers' ability to invest in improved technologies, labor-intensive pest control practices, and measures to adapt to climate change. Persistent low productivity levels heighten the risk of farm abandonment or diminished investment in coffee cultivation over time. Moreover, inadequate extension services and poor stakeholder coordination exacerbate these challenges by weakening institutional capacity. With an estimated extension agent-to-farmer ratio of approximately 1:400, the delivery of technical support and the dissemination of vital knowledge are significantly hampered. The fragmentation of producer groups further restricts opportunities for collective learning, coordinated pest control initiatives, and effective information sharing. Additionally, the absence of an integrated pest surveillance network and a functional early-warning system connected to research institutions limits the timely detection and response to emerging pest threats. This has contributed to the widespread underdevelopment of institutional frameworks essential for proactive climate adaptation. The most severe constraint across all dimensions examined is technological capability. However, the adoption of modern pest monitoring systems, biological control technologies, trapping techniques, and other contemporary Integrated Pest Management (IPM) tools remains extremely limited, with fewer than 5% of producers reportedly utilizing these methods **(MEWA, 2023).** In areas where chemical insecticides are applied, application is often fraught with poorly timed applications, poor product choice and use of broad-spectrum compounds that can disrupt communities of beneficial arthropods and natural biological control. Such practices may compromise long-term pest suppression, reduce agroecosystem resilience, and increase future outbreak risk. Altogether, these technological gaps would severely limit the ability of Khawlani coffee farmers to adapt well to the increasing pest pressures under projected climate change.

6. Climate-Smart Integrated Pest Management Strategies for Sustainable Khawlani Coffee Production in Jazan.

6.1. Pest Surveillance Systems and Climate-based Early Warning Networks

An essential element of climate-smart Integrated Pest Management (IPM) and increasingly accepted as a prerequisite for sustainable agricultural adaptation under climate change, is the establishment of comprehensive pest surveillance systems integrated with climate-based forecasting mechanisms **(Kairo *et al*., 2003 and Anderson *et al*., 2004).** The automated meteorological stations currently managed by the National Center for Meteorology (NCM) serve as a crucial foundation for establishing an early warning system aimed at safeguarding Khawlani coffee production. This system could play a significant role in forecasting pest outbreaks and enabling timely, effective management strategies. One innovative method under consideration involves the application of degree-day accumulation models, which rely on the thermal biology of the coffee berry borer (Hypothenemus hampei). Given that the pest's development is influenced by a lower thermal threshold of approximately 15°C, these temperature-driven forecasting models can help estimate generational cycles, predict seasonal population surges, and pinpoint periods of heightened infestation risk. This approach is supported by research findings **(Baker, 1999 and Jaramillo *et al*., 2009).** These predictive frameworks would allow proactive decision making and improve the timeliness of pest management operations. Monitoring of meteorological conditions should be complemented with systematic field surveillance using alcohol-baited traps with the standard methanol–ethanol attractant mixture (3:1 ratio). Distributed over representative coffee-growing zones and elevational gradients, sentinel monitoring sites would allow for the continuous assessment of pest abundance, detection of newly established populations and validation of forecasting outputs **(Dufour *et al*., 2013).** A regional monitoring network of about twenty strategically selected villages will probably provide adequate spatial coverage for effective surveillance and risk assessment. The information produced by surveillance and forecasting activities should be disseminated through mobile-based advisory systems such as Short Message Service (SMS) and smartphone applications to make it accessible and useful for practical purposes. Similar methods have proven effective in enhancing pest management results for smallholder farmers across various African agricultural systems. This has been achieved through the delivery of location-specific guidance and real-time alerts (**Davis *et al*., 2010 and Osei-Bonsu *et al*., 2019)**. Given the high penetration of mobile communication technologies in Saudi Arabia, digital advisory platforms hold much promise for enhancing the adaptive capacity of coffee producers. Such a system will require strong institutional coordination among MEWA, NCM, Jazan University and local agricultural cooperatives for long-term sustainability. Embedding surveillance activities into existing rural development programmes will be critical for continuity, operational effectiveness and long-term resilience, rather than relying on short-term externally financed projects (**Kairo *et al*., 2003).**

6.2. Cultural Control and Sanitation-Based Pest Suppression

Cultural management practices offer one of the most environmentally sustainable and economically feasible ways to suppress populations of coffee-associated insect pests. The primary goal is to disrupt pest life cycles by removing breeding and overwintering habitats, which allow their populations to persist between production seasons (**Damon, 2000 and Vega *et al*., 2015).** Among the most effective cultural practices for reducing coffee berry borer infestations is post-harvest sanitation, also referred to as repasa or completion harvesting. This approach involves systematically removing all residual fruits from coffee trees and collecting fallen berries after harvest. By doing so, it eliminates key reproductive reservoirs that pests rely on during periods of fruit scarcity. In Khawlani coffee production systems, these sanitation efforts should not only focus on the field but also extend to post-harvest processing facilities. While traditional dry-processing methods are essential for maintaining the unique quality attributes of Khawlani coffee, they can unintentionally create favorable conditions for pest survival if dried fruits are left for extended durations on drying platforms, in storage areas, or at processing sites. Therefore, sanitation through the entire production and processing chain is needed for effective pest suppression. Demographic aging and the decline of the rural workforce have led to labor shortages that present constraints on the successful implementation of sanitation programs. Cooperative and community-based approaches may therefore offer a more feasible and sustainable alternative. In major coffee-producing countries such as Guatemala, Rwanda and Indonesia, area-wide sanitation programs involving the joint participation of neighbouring farmers have been very successful in controlling populations of the coffee berry borer **(Bacon *et al*., 2008 and Vega *et al*., 2015).** Similar participatory models in Jazan could greatly improve collective pest suppression and reduce individual labor demand.

6.3. Biological Control with Indigenous Natural Enemies

Biological control is a keystone of sustainable IPM programs and has great potential to reduce dependence on synthetic insecticides in Khawlani coffee systems. Entomopathogenic fungi, especially Beauveria bassiana (Balsamo-Crivelli) Vuillemin, have been of great scientific interest worldwide among the biological control agents tested against coffee pests due to their proven efficacy against the coffee berry borer **(Bustillo-Pardey, 2006 and Vega *et al*., 2015).** Recent research within the Sarawat Mountain ecosystem has yielded promising findings regarding the effectiveness of indigenous B. bassiana isolates. Experimental trials show that locally obtained strains achieved mortality rates of almost 70% against adult coffee berry borers. These results match or even surpass the efficacy reported for various commercially available formulations **(MEWA, 2023).** The better performance of the native isolates is probably due to local adaptation to the prevailing environmental conditions, including temperature regimes, humidity patterns and intensity of solar radiation (**Inglis *et al*., 2001 and Meyling & Eilenberg, 2007).** Thus, developing locally produced fungal bioinsecticides based on indigenous strains offers a promising strategy to improve regional capacity for pest management and reduce dependence on imported biological products. Collaboration with MEWA and private-sector biotech companies could help Jazan University to commercialize and deploy such products at scale. Another potential biological control agent is the parasitoid Phymastichus coffea LaSalle

(Hymenoptera: Eulophidae) which parasitizes adult female coffee berry borers within infested berries. The successful establishment and implementation of this approach in various coffee-producing countries has highlighted its potential for effectively suppressing pest populations over the long term **(Murphy & Moore, 1990 and Bustillo-Pardey, 2006).** However, introducing it to Saudi Arabia would necessitate comprehensive ecological risk assessments, biodiversity evaluations, and the development of specialized mass-rearing facilities to guarantee both environmental safety and operational viability.

6.4. Agroforestry-Based Shade Management and Habitat Diversification

Agroforestry-based shade management and habitat diversification are increasingly recognized as valuable strategies for climate adaptation. These approaches hold the dual benefit of enhancing ecological resilience and promoting biodiversity conservation while contributing to pest control in coffee agroecosystems **(Lin, 2010 andJezeer *et al*., 2017).** On traditional Khawlani coffee farms, diverse shade-tree species, such as Juniperus procera and various types of Acacia, are already present. These trees provide crucial ecosystem services and help regulate the microclimate. Their canopies reduce temperature extremes and solar radiation, creating cooler microenvironments—approximately 2–4°C lower than surrounding open-field conditions. This moderation of temperature can hinder pest development rates and reduce the environmental suitability for numerous thermophilic insect species **(Perfecto *et al*., 1996 and Soto-Pinto *et al*., 2000).** Ensuring sufficient canopy cover is a key strategy for mitigating risks from climate-driven pests. Research indicates that when canopy cover drops below approximately 30%, agroforestry systems lose their effectiveness in regulating the microclimate and supporting biological control processes. Consequently, adaptation planning efforts should focus on preserving existing shade trees and restoring degraded canopy structures. Significant advantages can also be achieved by incorporating multipurpose tree species such as Cordia africana Lam, which has been successfully integrated into coffee farming systems across East Africa. Beyond offering suitable shade, this tree species provides timber, livestock fodder, carbon sequestration benefits, and additional income opportunities for farming households **(Tadesse *et al*., 2014).** Such diversified agroforestry systems enhance both ecological stability and socio-economic resilience in Khawlani coffee-growing landscapes. However, technical measures alone are insufficient to achieve long-term climate resilience without supportive institutional reforms and policy changes.

6.5. Institutional Reforms and Policy Priorities

Strengthening governance frameworks and agricultural support systems must be a fundamental part of climate-smart pest management strategies. A critical area of focus is redesigning agricultural subsidy programs to promote sustainable pest management practices. Traditional chemical pesticides are often incentivized by current support systems because of their availability and immediate benefits. However, excessive use of chemical control can result in accelerated development of resistance, harm to beneficial insect populations, increased environmental contamination and loss of compliance with emerging standards of sustainability **(Dufour *et al*., 2013).** Redirecting financial incentives to biological control agents, monitoring technologies, and IPM training programs would promote wider adoption of environmentally sustainable management approaches. Subsidies for alcohol-baited traps, indigenous B. The development of bassiana formulations and implementation of farmer capacity building initiatives could greatly improve pest management results and reduce long term production risks. Future extension and pest management programs should incorporate gender responsive policies. Despite women's major contribution to harvesting, processing and post-harvest handling, their role remains under-represented within formal agricultural support systems. The experiences of Africa, Latin America and Southeast Asia have shown that women's organizations often show high participation, technology adoption and monitoring success, when provided with appropriate institutional support **(FAO, 2011 and Boserup, 1989).** Therefore, greater participation of women in surveillance and extension activities could improve the overall success of pest management programmes. Pest management requirements should also be integrated into the developing Khawlani Geographical Indication (GI) certification framework. Certification standards that include regular monitoring, record-keeping, and compliance with IPM protocols will provide market incentives to recognize sustainable production practices and enhance product quality and environmental stewardship (**Bramley *et al*., 2009).** Finally, a strategic priority for adaptation is to increase the involvement of young people in the coffee sector. Initiatives that enhance access to land, agricultural finance, entrepreneurship opportunities and vocational training can help to address demographic imbalances and promote intergenerational continuity. Such investments will be critical to ensure the long-term competitiveness, innovation capacity and resilience of the Khawlani coffee sector under future climatic conditions.

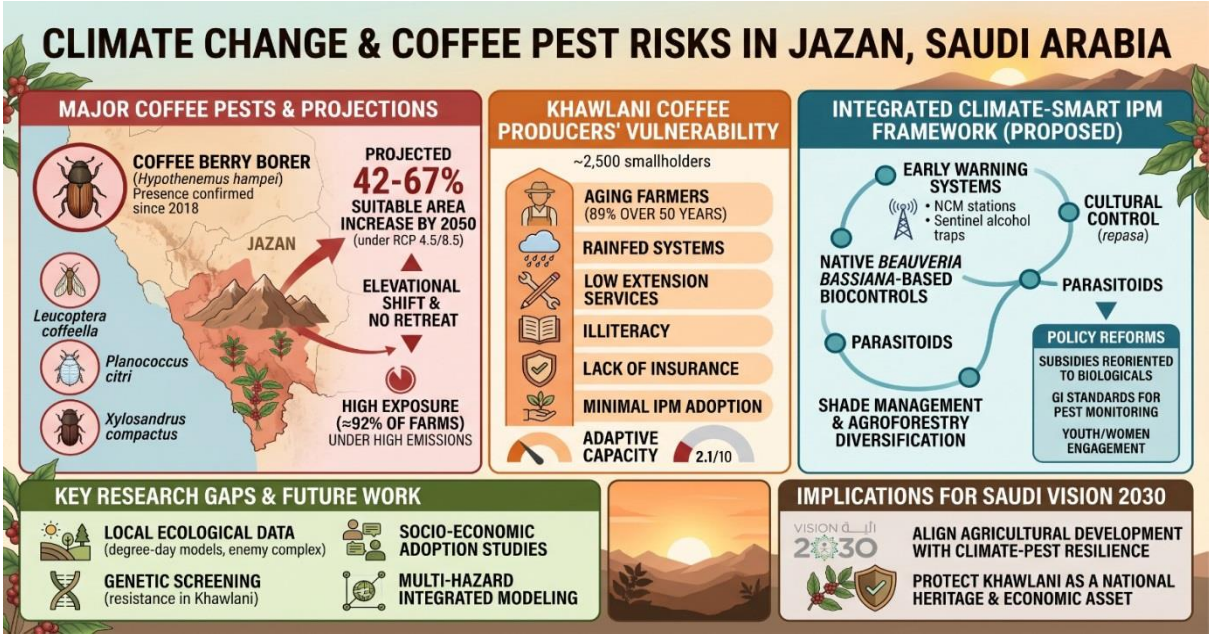

Figure: The figure summarizes an integrated assessment of climate change impacts on coffee pest risk and smallholder vulnerability in Jazan, including projected expansion of coffee berry borer suitability (42–67%) and an elevational shift by 2050. It also reflects low adaptive capacity of Khawlani farmers (2.1/10) because of socioeconomic and institutional constraints. Finally, it proposes a climate-smart IPM framework that combines biological control, early warning systems, shade management and policy support in line with Vision 2030.

7. Knowledge Gaps and Future Research Directions

7.1. Ecological Knowledge Gaps and Baseline Biological Data Needs

While there is increasing concern regarding climate-mediated pest risks in Khawlani coffee production systems, the development of scientifically sound pest management strategies is hampered by large gaps in locally generated ecological data. One of the most important among these is the lack of thorough studies on the population ecology, phenology and climatic responses of the major coffee pests. Although the coffee berry borer (Hypothenemus hampei) has become a major threat to coffee production in Jazan, nearly all the available forecasting frameworks are based on developmental parameters and ecological assumptions from populations studied in Latin America and East Africa. The biological parameters may not be directly transferable due to the specific environmental conditions of the Sarawat Mountain agroecosystem. Reliable phenological models for particular regions will necessitate long-term ecological studies covering multiple production cycles and climatic conditions. Future research should incorporate high-resolution microclimatic monitoring alongside systematic sampling of pest populations to evaluate seasonal fluctuations in the abundance of eggs, larvae, pupae, and adults across various elevations, management practices, and habitat types (**Baker, 1999 and Jaramillo *et al*., 2009).** These datasets are essential for calibrating models that predict pest outbreaks, improving the precision of pest forecasting, and informing context-specific, data-driven management strategies tailored to local environmental conditions. The second major knowledge gap is related to the composition, diversity and ecological function of natural enemy communities associated with coffee pests in Jazan. A large body of research carried out in Latin America and Africa has demonstrated the importance of parasitoids, predators and entomopathogenic microorganisms in the regulation of populations of H. hampei and other economically important coffee pests (**Bustillo-Pardey, 2006 and Murphy & Moore, 1990).** However, such ecological information is almost completely lacking for Saudi Arabian coffee agroecosystems. As a result, the abundance, distribution, and biological control potential of indigenous natural enemies are poorly known. This absence of baseline ecological information has important implications for pest management planning. Specifically, it restricts the evaluation of biological control opportunities and complicates the decision to introduce exotic natural enemies. Without a clear understanding of existing assemblages of parasitoids and predators, the success of establishment, competitive interactions and ecological consequences of introduced species such as Phymastichus coffea is highly uncertain. Thus, addressing these gaps in ecological knowledge should be a key research objective to underpin sustainable and climate resilient coffee production systems in Jazan.

7.2. Genetic Improvement and Screening for Pest Resistance

A systematic understanding of the genetic resources present in the traditional Khawlani landrace will be needed to improve the resilience of Khawlani coffee to future pest pressures. Identification and development of pest-resistant or pest-tolerant genotypes is a potentially valuable long term adaptation strategy, but progress on this front is currently hampered by the lack of a comprehensive genetic and phenotypic characterization of existing germplasm resources. Studies in Ethiopia and other centers of Coffea arabica diversity have revealed large variation in susceptibility to coffee berry borer infestation among wild and cultivated coffee populations. Resistance mechanisms have been related to several plant traits such as endosperm hardness, biochemical composition, and levels of defensive phenolic compounds (**Guerreiro-Filho, 2006 and Medina *et al*., 2019).** It is unknown whether similar sources of resistance are present within Khawlani coffee populations, as no systematic screening programs exist. Thus, establishing a comprehensive germplasm evaluation initiative should be a major research priority. These efforts should include molecular characterization techniques and field and laboratory evaluations of resistance-related traits such as antixenosis, antibiosis, and tolerance mechanisms. This work builds on a strong institutional basis of existing germplasm collections at MEWA's Jazan Agricultural Research Center and advanced molecular and genomic research facilities at Jazan University and King Abdulaziz University. In the long-term, the development of a specific Khawlani coffee breeding program focused on pest resistance, climate resilience, and agronomic performance could significantly contribute to the sustainability of the sector. While it is true that breeding projects generally require long-term investment over several years (often over 10 years), these are in line with the strategic direction of the Saudi Vision 2030 and national goals for agricultural sustainability.

7.3. Socioeconomic and Behavioral Dimensions of Adaptation

The effectiveness of pest management strategies is contingent not solely upon their technical performance but also upon their endorsement, implementation, and sustained utilization by agricultural practitioners. There is therefore a need for more research on social, economic and behavioral aspects of adaptation in the Khawlani coffee sector. One key priority is to understand the willingness of farmers to adopt climate-smart pest management technologies. Economic studies assessing willingness-to-pay for monitoring systems, biological control products based on Beauveria bassiana and community-based sanitation programmes would provide valuable information for designing subsidy frameworks, pricing mechanisms and extension strategies. Such analyses could help to identify financial and behavioral constraints on the adoption of improved pest management practices and thus improve the effectiveness of future intervention programs (**Feder *et al*., 1985; Anderson and Feder, 2004)**. The study of factors that influence the participation of young people in coffee farming is also important. The aging demographic structure of the farming population is a major challenge to the long-term sustainability of Khawlani coffee production. Future research should therefore examine perceptions of agricultural livelihoods among younger generations, barriers to participation in the coffee sector and assess policy measures that could improve the economic attractiveness and social status of farming compared to alternative employment opportunities. The remedy to these problems is to use more extensively social-science approaches in agricultural research. Household surveys, focus group discussions, participatory rural appraisal techniques, in-depth interviews and scenario-planning exercises can offer useful insights into farmers' behaviour, institutional constraints and adaptation preferences. Such interdisciplinary approaches are essential to understanding the human dimensions of climate adaptation and ensuring that technical innovations are aligned with the realities of rural livelihoods.

7.4. Development of Integrated Multi-Hazard Modeling Frameworks

A limitation identified in climate change research regarding coffee production is the tendency to assess individual stressors in isolation. Most studies look at pest outbreaks, drought events, plant diseases or market fluctuations in isolation, even though these factors often interact in complex socio-ecological systems. In fact, Khawlani coffee farmers face multiple, interconnected risks at the same time. Climatic variability exerts a significant influence on water accessibility, the physiological responses of crops, the dynamics of pest populations, and the associated costs of production, whereas prevailing market conditions play a pivotal role in shaping investment choices, management approaches, and the resilience of households. The interaction among these stressors often leads to consequences that are inadequately addressed by assessments considering only individual stressors. Consequently, forthcoming research endeavors should prioritize the formulation of integrated modeling frameworks that are adept at encapsulating the multifaceted characteristics of climate-related risks. The amalgamation of process-oriented crop simulation models with pest population dynamics, hydrological forecasting methodologies, and agent-based models reflecting farmer decision-making processes would yield a more accurate and holistic foundation for the appraisal of prospective adaptation scenarios **(Rippke *et al*., 2016; Tesfaye *et al*., 2018 and Pham *et al*., 2021).** Such frameworks would facilitate the evaluation by scientists and policymakers of the complex interrelations among climate change, water scarcity, pest infestations, economic fluctuations, and management strategies, all of which impact agricultural productivity and rural livelihoods over time. The establishment of sophisticated modeling systems for Jazan will necessitate considerable investments in enduring monitoring initiatives, computational infrastructure, and specialized scientific proficiency. Consequently, international collaboration ought to be an essential element of forthcoming research methodologies. Partnerships with institutions possessing extensive expertise in coffee systems research, particularly in nations such as Ethiopia, Colombia, and the Netherlands, may foster knowledge dissemination, methodological advancements, and capacity enhancement. At the same time, development of domestic scientific capacity remains an important element in the long-term sustainability of research efforts. Investment in graduate education, interdisciplinary training, and specialized expertise in climate science, ecological modeling, pest management, and agricultural systems analysis will be essential to establish a durable scientific foundation on which to base evidence-based management of emerging climate-related challenges. This capacity building will enhance Saudi Arabia's ability to develop context specific solutions and ensure long-term resilience of Khawlani coffee production to climate change.

8. Synthesis and Concluding Perspectives

8.1. Synthesis of Major Findings

This review synthesizes evidence from climate science, insect ecology, species distribution modelling (SDM), agricultural economics and rural development research to assess potential impacts of climate change on Khawlani coffee production systems in Jazan, Saudi Arabia. The integrated assessment shows that climate change is likely to increase the threat from insect pests and expose existing socioeconomic vulnerabilities of coffee-growing communities, posing a major risk to the long-term sustainability of this unique agricultural heritage system. The most important climate sensitive threat to Khawlani coffee production among the pest species assessed was the coffee berry borer, Hypothenemus hampei. The pest has been confirmed in major coffee-producing districts such as Al-Dayer and Faifa and, because it is highly temperature dependent, there is a high potential for it to increase in numbers in the future. Species distribution modeling projections show a large increase in climatically suitable habitat by 2050, from about 42% under the intermediate-emissions scenario (RCP 4.5) to 67% under the high-emissions scenario (RCP 8.5). Importantly, the predictions indicate an increase in suitable habitat in higher elevation coffee-growing regions, which currently serve as partial refuges from high pest pressure. In addition to the coffee berry borer, other pest species such as Leucoptera coffeella, Planococcus citri and Xylosandrus compactus are also expected to increase in importance in the future climatic conditions. Their developmental rates, survival and geographic distribution are expected to accelerate with rising temperatures and changed precipitation patterns, though their current impacts are still relatively limited. Therefore, future pest management strategies should be directed towards the whole pest complex rather than focusing on a single species. The vulnerability assessment also found that farmers growing Khawlani coffee are highly vulnerable to climate-related pest risks. The vulnerability is due to synergistic effects of high dependency on rainfed agriculture, narrow genetic base of the Khawlani landrace, aging farming community, low institutional support, limited access to financial services and low adoption of modern technologies for pest management. The estimated adaptive capacity index of 2.1/10 indicates that existing capacities are not sufficient to cope effectively with projected increases in pest pressure without significant external support and institutional intervention. In this review, an integrated climate-smart adaptation framework is proposed to tackle the above challenges. The framework is a combination of climate-based pest surveillance system, sanitation-oriented cultural practices, biological control using indigenous Beauveria bassiana isolates, agroforestry-based shade management and targeted policy reforms. These measures collectively offer a scientifically sound way to improve resilience while preserving the ecological integrity and cultural value of Khawlani coffee production systems. The urgency of such interventions is made clear by projections that indicate potential yield decreases of about 25 – 40% by 2050 under scenarios with limited adaptation measures. Not only would household incomes be affected by such losses, but broader national objectives on rural development, agricultural diversification, biodiversity conservation and cultural heritage preservation could also be undermined.

8.2. Implications for Vision 2030 and Agricultural Policy

The results of this review have direct implications for the strategic goals of Saudi Arabia's Vision 2030 that recognizes Khawlani coffee as a priority commodity for rural development, agricultural diversification, and heritage conservation. Much has already been invested in strengthening the sector through infrastructure development, farmer support programs, market expansion initiatives and value-chain enhancement projects. However, the long-term effectiveness of such investments may be in jeopardy unless climate-related pest risks are routinely incorporated into future planning and policy frameworks. Climate adaptation and pest management considerations need to be integrated at all stages of agricultural development planning to ensure sustainability and competitiveness of the Khawlani coffee sector. Pest risk assessments should be integrated into seedling distribution programs, farmer training programs, certification systems, extension services and infrastructure development projects. This integration would increase the resilience of coffee production systems without compromising the large public investments already made for sectoral development. Achieving this goal will require better cooperation between governmental agencies, research institutions, extension services and producer organizations. In particular, strengthened collaboration between climate scientists, entomologists, agronomists and rural development specialists will be crucial to generate evidence-based adaptation strategies and support proactive decision-making. Interdisciplinary collaboration and long-term institutional engagement can integrate climate resilience as a key component of the coffee sector's future development in Saudi Arabia.

9. Conclusion

Khawlani coffee is one of the most unique agricultural heritage resources of Saudi Arabia, reflecting centuries of traditional knowledge, cultural identity and ecological adaptation in the Sarawat Mountain area. The combined effects of climate change, increasing pressure from insect pests, demographic shifts within farming communities, and institutional constraints that limit adaptive responses, are challenging the sustainability of this production system, which is of increasing economic and strategic importance. The reviewed evidence suggests that climate change is likely to increase the distribution and severity of important coffee pests, particularly the coffee berry borer, and at the same time create favorable conditions for the emergence and establishment of additional pest species. These biological threats are likely to compound existing socio-economic vulnerabilities and thus increase the overall risk profile of Khawlani coffee production systems over the coming decades. But the review also highlights significant opportunities for adaptation. Practical and scientifically supported ways to reduce vulnerability and enhance resilience are provided by climate-smart Integrated Pest Management (IPM) strategies such as early warning systems, biological control, sanitation-based cultural practices, agroforestry diversification, and enhanced extension services. Crucially, many of these approaches are compatible with traditional characteristics of Khawlani coffee farming and can be implemented without compromising the cultural and heritage value of the crop. The next ten years will be decisive in determining the future path of the Khawlani coffee industry. The sector's future resilience to environmental threats will depend on investment in pest surveillance infrastructure, biological control research, farmer capacity building, climate adaptation planning and institutional strengthening. Delaying the implementation of adaptation measures is likely to increase economic losses and future management costs. Ultimately, the long-term sustainability of Khawlani coffee will depend on the extent to which climate resilience is integrated into agricultural policy, research agendas and rural development programmes. With continued commitment, wise investment, and strong cooperation between policy makers, researchers, extension agencies, and the farming community, Khawlani coffee can remain a beacon of Saudi Arabia's agricultural heritage, rural prosperity, and environmental resilience. However, the failure to address emerging climate–pest interactions may put this unique production system at increasing risk, threatening both its economic viability and its cultural legacy for future generations.

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