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COMPREHENSIVE REVIEW ON ROLE MICROCLIMATE MODIFICATION FOR CROP PEST AND DISEASE INCIDENCE UNDER ELEVATED TEMPERATURE CONDITIONS

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ABSTRACT
Global surface temperatures have risen significantly over the past several decades, leading to an increased frequency of extreme heat events that threaten global food security and crop physiological stability. While macroclimatic data provide broad environmental trends, the health and productivity of crops are more directly governed by the microclimate, especially environmental conditions including temperature, humidity, and radiation within the cropping systems. This review explores the importance of microclimate modification as a resilient approach to mitigate the combined impacts of elevated temperatures and biotic stressors. Higher temperatures directly impair critical reproductive processes, such as pollen viability and grain filling, while simultaneously accelerating the metabolic rates and reproductive cycles of insect pests and enhancing the virulence of various pathogens. We categorize microclimate management into two primary strategies: protected cultivation and vegetative modification. Protected structures, such as greenhouses and shade nets, offer high-precision control over thermal and moisture variables while providing physical barriers against pests. Nature-based vegetative interventions, including intercropping, agroforestry, and shelterbelts, utilize shading and transpiration cooling to buffer thermal extremes and enhance biodiversity. By modulating canopy temperature, humidity, and airflow, these modifications reduce the risk of pest proliferation and disease outbreaks while optimizing water-use efficiency. Integrating microclimate management with resistant crop varieties and sustainable pest control is essential for developing resilient agricultural systems capable of sustaining productivity in an increasingly unpredictable or extreme climate.

KEYWORDS: Biotic stress, Climate-resilient, Elevated temperature, Heat stress, Microclimate modification, Protected cultivation.

INTRODUCTION

Over the last few decades, the global climate system has warmed rapidly, with average surface temperatures rising significantly above their pre-industrial levels due to higher levels of greenhouse gas emissions [1]. This warming trend has accelerated the frequency of heat stress events, which increasingly threaten global food security and crop physiological stability [2]. Numerous observational datasets and reanalysis products demonstrate that the past decade has been the warmest on record, with 2023 ranking as one of the hottest years globally, marked by exceptional land and marine heat waves and an amplified occurrence of temperature extremes [3]. Figure 1 illustrates how this elevated temperature signal is filtered through seven microclimatic variables- canopy air temperature, leaf-surface temperature, relative humidity, vapour pressure deficit, boundary-layer wind speed, photosynthetically active radiation and soil surface thermal status, each of which can differ substantially from measurements made at standard screen height [4].

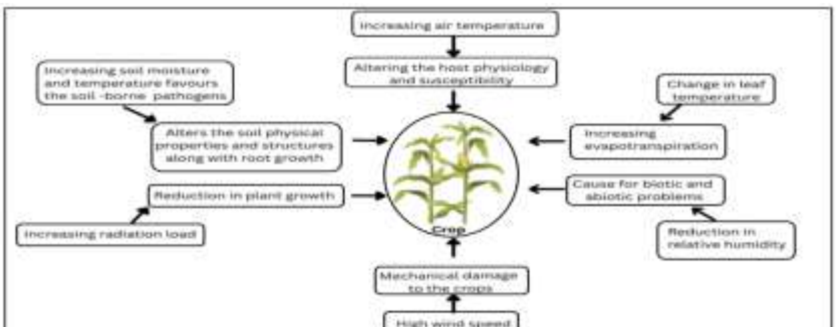

Fig. 1 — Conceptual schematic of microclimatic factors acting on a crop canopy under elevated ambient temperature.

Variables like air temperature inside and above the canopy, leaf temperature, relative humidity, wind speed, radiation load, and soil surface conditions are all included in the term "microclimate", and they can all differ significantly from measurements made at standard screen height in neighbouring weather stations [4]. For example, bare soil and sparse canopies can result in higher daytime temperatures and a larger vapour pressure deficit at the leaf level, whereas dense canopies can produce cooler and more humid conditions close to the soil surface compared to ambient air [5]. Because many physiological systems, as well as the infection and growth of pests and pathogens, respond to microclimatic rather than macroclimatic circumstances, these fine-scale variations are crucial for predicting the development of biotic stresses, as they dictate the virulence of pathogens and the population dynamics of insect pests [6], [7]. Figure 2 identifies four categories of factors that jointly govern the crop-canopy microclimate: cropping system, canopy architecture, cropping stages and ecosystem type (garden-land, wetland and dryland). The convergence of these four drivers at a single canopy-state variable [4] frames the same microclimate that subsequently determines the leaf-scale responses of pests [8], pathogens [9] and vectors [1]. Together with the seven microclimatic variables identified in Figure 1, this state-variance approach provides the conceptual scaffolding that the synthesis below develops [5], [6], [10], [11].

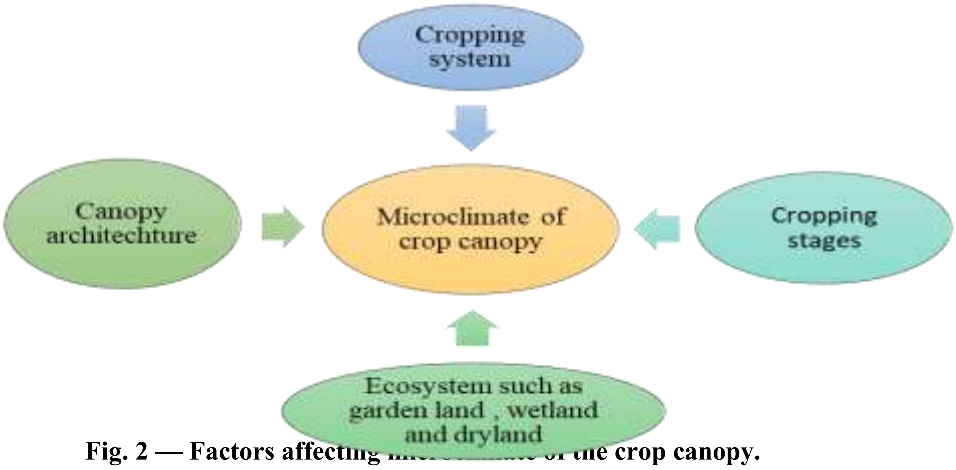

Fig. 2 — Factors affecting microclimate of the crop canopy.

The canopy temperature depends on a number of factors, including radiation balance, transpiration cooling, boundary layer characteristics, and canopy architecture. As a result, when there is intense radiation or little transpiration, leaf temperature can differ from air temperature by several degrees [12].

Consequently, understanding the interplay between these environmental variables and crop traits is essential, as canopy structure can effectively attenuate macroclimatic extremes to provide a buffer for organisms residing within the vegetation layer [13]. Fine-scale environmental variations within crop canopies significantly influence the behavior and development of pathogens and insect pests [7]. Alterations in microclimatic factors—such as temperature, humidity, and airflow—directly regulate critical biological processes, including spore germination, the success of pathogen infection, the rate of pathogen proliferation, as well as the foraging, survival, and population dynamics of insect pests [6], [7]. Even slight changes in microclimate can influence the degree of plant defence or disease pressure changes as these processes are so sensitive to their immediate surroundings. Managing microclimate, therefore, offers a practical way to soften the effects of rising temperatures on crop health. Microclimate modification such as mulching, shading, intercropping, shelterbelts and agroforestry, along with newer options like shade nets, greenhouses, and screen houses, to moderate heat and humidity around crops [14]. These practices can lower canopy temperatures, reduce daily heat fluctuations and alter wind and moisture conditions, which also affect how vectors and airborne pathogens move and survive [7]. Microclimate management, when integrated with resistant varieties, biological control, or targeted chemical applications, serves as a critical component of climate-resilient pest and disease control [15].

The unexpected weather conditions and their frequent dynamics are predisposing the agriculture and horticultural crops to biotic stress. The elevated temperatures during the hot summer are a major threat to the productivity of the crops. Research shows that combined heat and biotic stresses trigger complex plant responses that differ from effects of individual stress [16]. This review, therefore, focuses on how microclimate modification can support the management of biotic stress under elevated temperatures, with attention to climate impacts on crops, heat induced changes in pest and pathogen behaviour, their adaptive responses and the range of structural and vegetative interventions suitable for different cropping systems.

2. Biotic Stress Due to Climate Variation in Agriculture

The increasing prevalence of heat-induced physiological stress facilitates the migration and proliferation of diverse pests and pathogens, often expanding their range into previously affected agro-ecological zones [6]. Biotic stresses arising from fungi, bacteria, viruses, insect pests, nematodes, and weeds remain among the most serious constraints on agricultural productivity, often leading to significant losses in both yield and quality [17]. Climate change is reshaping these stressors by altering the biology, distribution, and population dynamics of harmful organisms, often intensifying the damage they cause to crops [6]. Receiving a clearer understanding of these shifting interactions is crucial for developing adaptive management approaches that can sustain crop production in a warming world [18]. Rising temperatures and increasingly erratic rainfall influence biotic stressors through a variety of mechanisms. Warmer conditions speed up the growth and reproduction of many pests and pathogens, allowing them to expand into new regions including higher latitudes and altitudes and modify their seasonal timing. At the same time, these climatic shifts can alter plant physiology and immunity, affecting the susceptibility of crops to infections and pest attacks [7], [19]. Milder winters, for instance, enable numerous insects and pathogens to persist in areas where they previously could not survive, leading to earlier and more severe infestations during the crop season [6]. Changing humidity and rainfall patterns also influence disease outbreaks by affecting key infection processes such as spore germination and dispersal [6].

Fungal pathogens, for instance, are increasingly showing altered virulence and enhanced heat tolerance in some species, leading to shifts in their communities as temperature rise [20]. Similarly, bacterial diseases exhibit a concerning trend where their virulence gene expression becomes temperature dependent. This means they can exploit the weakened resistance of host plants experiencing heat stress, making them more dangerous [9]. Viral diseases, often spread by sap-feeding insects, are also experiencing a boost. Both the populations of their insect vectors and the rate at which viruses replicate tend to accelerate with warmer temperatures, dramatically increasing the potential for disease transmission [1]. These interconnected processes illustrate how climate change is reshaping the relationships between hosts, pathogens, and vectors, thereby complicating effective disease prediction and management [21], [22].

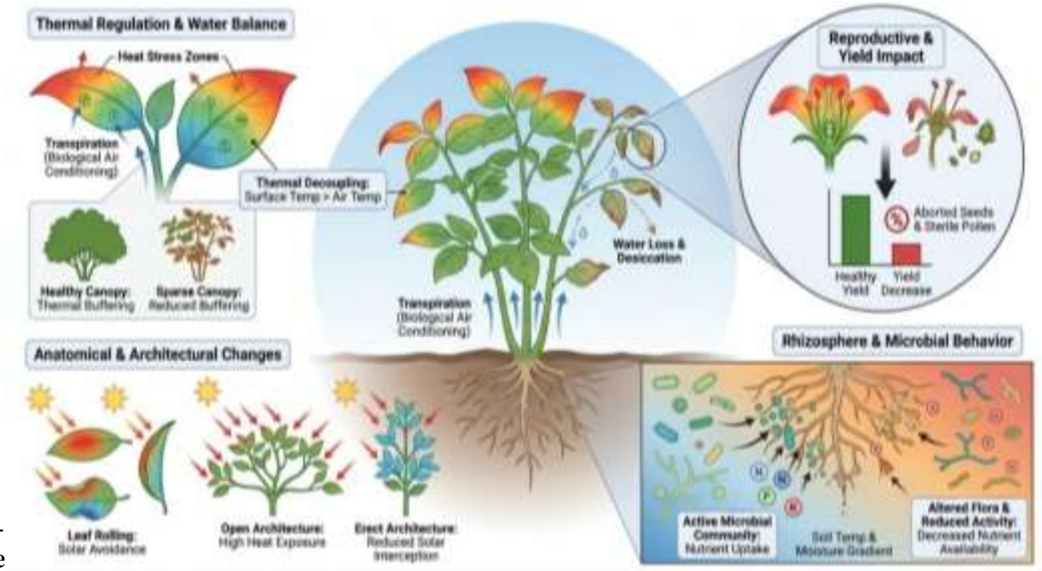

Fig. 3 — … es the impacts of e… oductive development, and yield formation

Insect pests particularly sap feeding species such as aphids, whiteflies, jassids, and thrips are increasingly thriving under warmer conditions. Rising temperatures accelerate their metabolic rates and shorten developmental cycles, which drives faster reproduction and more frequent generation turnover [7]. Beyond these physiological advantages, climate induced warming facilitates the expansion of their geographical ranges into higher latitudes and altitudes, while simultaneously enhancing the efficiency of viral transmission by these vectors, thereby compounding the threat to agricultural productivity [1], [7]. Research from India and other tropical regions has consistently shown a direct link between rising temperatures and higher population densities of these key sucking pests on vegetables and cereals. This not only causes more direct damage to crops but also accelerates the spread of plant viruses [23]. This alarming trend poses a serious threat to crop health and intensifies pest management challenges, particularly for smallholder farmers who have limited access to necessary resources [24], [25]. To mitigate these mounting pressures, the implementation of integrated pest management strategies alongside the development of heat tolerant and virus resistant crop varieties is essential to maintain food security [26].

Table 1. Thermal Thresholds and Biological Responses of Major Plant Pathogens

Sl No.	Crop	Disease	Favourable Temperature	Triggered Causative Organism	Response	Reference
1	Maize	Charcoal rot	32–35 °C	Macrophomina phaseolina	Favours sclerotia production under elevated heat	[1], [2]
2	Soybean	Charcoal rot	32–35 °C	Macrophomina phaseolina	Optimal for disease development; microsclerotia germinate rapidly	[1], [2]
3	Chickpea	Dry root rot	30–35 °C	Macrophomina phaseolina	Conducive for root necrosis	[1], [2]
4	Banana	Tip-over / Erwinia rot	30–34 °C	Pectobacterium carotovorum subsp. carotovorum	Enhances pectolytic enzyme activity	[3]
5	Tomato	Bacterial wilt	30–35 °C	Ralstonia solanacearum	Supports high multiplication; 95.9–98.7 % wilt at 35 °C	[3], [4]
6	Chilli	Bacterial leaf spot	30–32 °C	Xanthomonas euvesicatoria	Optimum for leaf lesions; severity rises with T	[3]

7	Groundnut	Bacterial wilt	30–34 °C	Ralstonia solanacearum	Stimulates infection and vascular colonisation	[3], [4]
8	Cotton	Cotton leaf curl	30–35 °C	CLCuV complex (Bemisia tabaci-vectored)	Enhances vector transmission efficiency	[5]
9	Okra	Yellow vein mosaic	30–34 °C	YVMV (whitefly-vectored)	Increases replication and transmission	[5]
10	Potato	Soft rot	30–33 °C	Pectobacterium/Dickeya spp.	Favours tuber maceration	[3]
11	Brinjal	Bacterial wilt	28–34 °C	Ralstonia solanacearum	Accelerates vascular colonisation	[3], [4]
12	Rice	Bakanae disease	28–32 °C	Fusarium fujikuroi	Stimulates sporulation and infection	[1]
13	Papaya	Ringspot disease	28–32 °C	PRSV (aphid-vectored)	Speeds systemic movement	[5]
14	Cucurbits	Watermelon mosaic	28–32 °C	WMV (aphid-vectored)	Favours symptom expression	[5]
15	Rice	Rice tungro disease	28–32 °C	RTSV + RTBV (leafhopper-vectored)	Favourable for vector activity and synergistic viral replication	[5]
16	Maize	Maize lethal necrosis	28–32 °C	MCMV + SCMV (synergistic)	Increases co-infection severity under warming	[5], [1]
17	Pigeonpea	Sterility mosaic	28–32 °C	PPSMV (eriophyid-mite-vectored)	Enhances mite vector proliferation and virus spread	[5]
18	Groundnut	Peanut bud necrosis	28–32 °C	PBNV (thrips-vectored)	Favours thrips transmission; viral load rises	[5]
19	Pomegranate	Bacterial blight	28–32 °C	X. axonopodis pv. punicae	Enhances epiphytic growth and lesion expansion	[3]
20	Sugarcane	Ratoon stunt	28–32 °C	Leifsonia xyli subsp. xyli	Supports multiplication in vascular tissue	[3]
21	Rice	Sheath blight	28–30 °C	Rhizoctonia solani	Promotes rapid lesion expansion	[6]
22	Maize	Stewart's wilt	28–30 °C	Pantoea stewartii subsp. stewartii	Favours systemic infection via flea-beetle vector	[3]
23	Maize	Fusarium ear rot	27–30 °C	Fusarium verticillioides	Speeds up colonisation of kernels	[1]
24	Mango	Anthracnose	27–30 °C	Colletotrichum gloeosporioides	Promotes fruit rot	[1]
25	Banana	Banana bunchy top	27–30 °C	BBTV (aphid-vectored)	Enhances aphid transmission	[5]
26	Rice	Brown spot	25–30 °C	Bipolaris oryzae	Enhances conidial germination	[7]
27	Tomato	Early blight	25–30 °C	Alternaria solani	Favours spore germination and lesion development	[1]
28	Soybean	Soybean mosaic	25–30 °C	SMV	Increases symptom expression	[5]
29	Wheat	Wheat streak mosaic	24–28 °C	WSMV (mite-vectored)	Increases viral load	[5]
30	Grape	Powdery mildew	22–28 °C	Erysiphe necator	Supports conidial germination	[8]
31	Pearl millet	Downy mildew	20–30 °C	Sclerospora graminicola	Increases sporangial release and zoospore infection	[1], [9]

Table 2. Impact of Elevated Temperature on Key Pests and Infestation Dynamics

Sl No.	Crop	Favourable Temp. (°C)	Pest Organism	Damage Type	Reference
1	Cotton	28–34 °C	Helicoverpa armigera	Bollworm infestation	[10], [11]
2	Cotton	28–35 °C	Bemisia tabaci	Whitefly outbreak / sooty mould	[12], [5]
3	Cotton	27–34 °C	Thrips tabaci	Thrips injury	[11], [1]
4	Brinjal	28–34 °C	Leucinodes orbonalis	Shoot & fruit borer	[13], [11]
5	Okra	28–35 °C	Bemisia tabaci	Whitefly infestation	[12], [5]
6	Okra	28–33 °C	Earias vittella	Shoot & fruit borer	[11]
7	Tomato	26–35 °C	Bemisia tabaci	Whitefly (virus vector)	[12], [5]
8	Tomato	24–32 °C	Tuta absoluta	Leaf miner damage	[14], [11]

9	Chilli	28–34 °C	Polyphagotarsonemus latus	Mite outbreaks	[11], [9]
10	Chilli	28–33 °C	Scirtothrips dorsalis	Thrips & orthotospovirus transmission	[11], [5]
11	Mango	30–34 °C	Amritodes atkinsoni	Mango hopper outbreak	[11]
12	Mango	30–34 °C	Bactrocera dorsalis	Fruit fly damage	[10], [11]
13	Banana	28–32 °C	Cosmopolites sordidus	Banana weevil borer	[14], [1]
14	Banana	28–32 °C	Pentalonia nigronervosa	Aphid	[12], [5]
15	Banana	29–34 °C	Thrips hawaiiensis	Thrips (fruit blemishing)	[11]
16	Rice	30–34 °C	Dicladispa armigera	Rice hispa outbreaks	[12], [11]
17	Rice	28–32 °C	Nilaparvata lugens	Brown planthopper	[12], [5]
18	Rice	28–32 °C	Cnaphalocrocis medinalis	Rice leaffolder	[12], [11]
19	Maize	28–32 °C	Spodoptera frugiperda	Fall armyworm	[15], [1]
20	Maize	30–34 °C	Chilo partellus	Stem borer	[15], [12]
21	Sorghum	28–33 °C	Stenodiplosis sorghicola	Sorghum midge	[11], [2]
22	Pearl millet	30–34 °C	Heliocheilus albipunctella	Millet head miner	[11], [13]
23	Pigeonpea	28–34 °C	Helicoverpa armigera	Pod borer damage	[10], [13]
24	Chickpea	28–34 °C	Helicoverpa armigera	Pod borer & defoliation	[10], [13]
25	Green gram	28–35 °C	Bemisia tabaci	Whitefly damage	[12], [5]
26	Black gram	28–33 °C	Thrips palmi	Thrips feeding	[11], [1]
27	Soybean	28–35 °C	Bemisia tabaci	Whitefly & leaf damage	[12], [5]
28	Soybean	30–34 °C	Tetranychus urticae	Mites (leaf bronzing)	[9], [11]
29	Groundnut	28–33 °C	Scirtothrips dorsalis	Thrips & leaf curl vectoring	[11], [5]
30	Groundnut	30–33 °C	Aproaerema modicella	Leaf miner	[11], [13]
31	Sugarcane	28–32 °C	Chilo infuscatellus	Early shoot borer	[15], [11]
32	Sugarcane	28–34 °C	Aleurolobus barodensis	Whitefly	[12], [11]
33	Tomato	30–34 °C	Tetranychus urticae	Spider mite injury	[9], [11]
34	Strawberry	30–35 °C	Tetranychus urticae	Spider mite	[9], [11]
35	Cassava	30–32 °C	Mononychellus tanajoa	Cassava green mite	[13], [2]
36	Cassava	28–32 °C	Phenacoccus manihoti	Mealybug	[13]
37	Citrus	28–32 °C	Diaphorina citri	Citrus psyllid	[5], [13]
38	Date palm	28–34 °C	Rhynchophorus ferrugineus	Red palm weevil	[1], [13]
39	Tea	28–33 °C	Helopeltis theivora	Tea mosquito bug	[11], [1]
40	Tea	30–34 °C	Oligonychus coffeae	Red spider mite	[9], [11]
41	Capsicum	30–34 °C	Polyphagotarsonemus latus	Broad mite	[11], [9]
42	Grapes	28–32 °C	Planococcus ficus	Mealybug	[13], [16]

3. Extreme Temperature and it’s Consequences

A growing body of global and regional research shows that rising temperatures, shifting rainfall patterns and increasing climate variability are already dragging down yields of major crops, even when technological improvements are taken into account [6]. Looking toward the mid-to-late 21st century, recent syntheses suggest that agricultural output in arid and semi-arid zones could decline by 10 to 25 per cent unless farmers successfully adapt to the combined pressures of heat and water stress [6].

At the crop level, heat accelerates plant development and shortens the window of growth while destabilizing delicate reproductive processes such as pollen viability and grain filling [14]. Heat bursts during flowering in cereals can cause disproportionately high losses, and prolonged warming during grain filling reduces starch accumulation, often producing poorly filled grains [6], [27]. Figure 4 arranges the developmental stage specific sensitivity of cereals, vegetables and pulses along a horizontal axis spanning germination, vegetative growth, anthesis, grain filling and maturation; the shaded reproductive stage columns indicate that heat stress during anthesis and grain filling disproportionately drives final yield loss — a conclusion drawn from the heat-stress physiology literature [10], [14], [27].

Fig. 4- Influence of elevated temperature on crop growth and its relationship with biotic stress incidence. The figure depicts how heat-induced physiological changes can alter host susceptibility, pathogen development, pest dynamics, and disease occurrence.

The frequent heat waves, droughts, heavy rainfall and floods now play a major role in causing sudden yield crashes and harvest failures [6]. Probabilistic studies show that the likelihood of reduced harvests in crops such as wheat increases sharply under high emission scenarios because extreme heat often strikes during the most sensitive crop stages [28]. Beyond damaging crops, these extremes disrupt sowing and harvesting schedules, strain rural infrastructure and interact with pests and diseases, creating risks that extend far beyond average yield changes [29].

Countries in the tropics and subtropics, especially India, face the highest risks because agriculture due to extreme weather [28]. National level assessments project 10 to 40 per cent declines in crop production by the end of the century, with wheat, rice and maize among the most affected [28], [30]. District level analyses further show that many Indian regions already fall into high another risk categories due to rising temperatures, erratic rainfall and limited adaptive capacity of smallholder farmers [31]. These environmental changes carry significant socioeconomic consequences. Reduced yields and greater production variability drive up food prices, destabilize farm incomes, and worsen poverty and malnutrition, especially in communities where most income is spent on food [15], [32]. Recent work shows that climate pressures also affect livestock productivity, rural labour, and household livelihoods, often forcing migration or deepening indebtedness among marginal farmers [33]. Taken together, national and international assessments point toward the same conclusion: without coordinated adaptation and mitigation efforts, climate change will increasingly undermine food security and slow progress toward sustainable development goals [6].

4. Threats due to Elevated Temperature

Crops have optimal temperature windows for growth and development, and deviation above these ranges during critical phenological stages can cause irreversible damage, particularly during reproductive phases [6], [34]. Furthermore, such thermal stress can compromise the host plant's internal defense signaling and secondary metabolic pathways, rendering crops more vulnerable to subsequent pathogen inoculation [8].

Heat stress during grain filling accelerates senescence and reduces carbohydrate translocation, resulting in shriveled grains and lower grain weight [35]. The phenological acceleration caused by increased temperature reduces length of the growing period and grain filling duration, limiting biomass accumulation [10], [36]. Elevated temperature also augments atmospheric vapor pressure deficit, intensifies evaporative demand, and frequently causes soil moisture deficits, which jointly exacerbate drought stress and impair photosynthetic efficiency and transpiration cooling ability [37]. These compounded abiotic stresses increase plant susceptibility to pathogens and pests by weakening defence mechanisms and altering plant physiology [38], [39].Elevated temperature, defined in agronomic literature as the chronic or episodic rise above a crop's thermally optimal envelope, is now one of the principal drivers of yield loss in the global cereals complex. Quantitative work on wheat exposed to heat stress (32/22 °C day/night) showed a 17 % reduction in photosynthetic rate during anthesis and a 25 % reduction during grain filling, accompanied by a 61–68 % increase in thylakoid membrane damage and grain yield losses of 29 % and 44 % in the same developmental windows respectively [10]. In wheat and other cereals, the reproductive phase is consistently identified as the most heat sensitive: a single three-day 38 °C heat wave event reduced photosynthesis transiently but had no lasting effect on vegetative growth, whereas the same heat event at reproductive stages caused significant yield reductions [40]. The physiological basis of this damage lies in chlorophyll and rubisco activase degradation [41], lowered net photosynthesis coupled to rising mitochondrial respiration [42], reduced seed-set through pollen sterility and anther indehiscence [10], and shortened grain filling windows as developmental cycles accelerate [42], [6]. Because rice, wheat, maize and soybean together supply roughly two-thirds of global human caloric intake [6], these stage specific losses translate into direct food security consequences, motivating the integrated microclimate modification approach developed later in this review [7], [27].

In addition to direct crop impacts, elevated temperature modifies biotic stress dynamics by accelerating pathogen life cycles, enhancing pest survival and reproduction, and altering host, pathogen and vector interactions, thereby intensifying disease and pest outbreaks [43]. Such outbreaks disrupt yield potential and increase reliance on chemical controls, potentially creating further ecological imbalance [20]. Crop specific studies demonstrate these threats with documented yield declines under elevated temperature conditions: severe heat stress reduced wheat yields by up to 40 per cent in South Asia, rice yield reductions of 10-30 per cent under episodic heat, and vegetable productivity decline in subtropical regions [31]. These losses collectively undermine food security and rural livelihoods, especially in climate vulnerable areas where farmers have limited adaptive capacity [44]. Overall, the threats posed by elevated temperature transcend simple yield loss and encompass complex physiological, ecological, and socioeconomic dimensions, necessitating integrated adaptation strategies that include microclimate modification, genetic improvement, and sustainable pest and disease management [45], [46].

5. Microclimate Modification

Microclimate modification involves deliberate alterations to the immediate environment surrounding crops, including temperature, humidity, radiation, and airflow, to alleviate heat stress and manage biotic pressures, thereby improving crop health and productivity under elevated temperature scenarios [5], [7]. Two broad categories dominate: protected cultivation structures such as greenhouses and shade nets, and vegetative modification using intercrops, border crops, shelterbelts, and agroforestry systems [47], [48].

Protected cultivation structures, including greenhouses, shade houses, plastic tunnels, and protective nets, provide precise control over temperature, humidity, and light, enabling significant reductions in canopy temperature and the adjustment of microclimatic variables to optimal levels for crop growth [49], [50]. These structures reduce heat and radiation load during the hottest parts of the day, stabilise humidity to prevent desiccation, and limit pest and pathogen entry through physical barriers [50]. However, they require considerable capital investment, technical expertise, and energy inputs for environmental control and maintenance [49], [50].

Vegetative modification structures use crops to naturally alter the microclimate by providing shade, reducing wind speed, enhancing humidity, modifying light quality, and blocking or diverting pest movement [51]. Intercropping and border cropping with compatible species lower canopy temperature through shading and transpiration cooling, improve soil moisture retention, and enhance biodiversity [52]. Tree based shelterbelts and agroforestry systems similarly buffer microclimate extremes, reduce evaporative demand, and provide habitat for beneficial organisms, thereby contributing to pest suppression and improved crop resilience [11]. Vegetative structures often create complex interactions that alter pathogen and pest dynamics. For instance, changes in microclimatic factors such as increased humidity and reduced wind speed can either mitigate or exacerbate disease epidemiology, depending on the specific pathosystem [52]. Nonetheless, vegetative modification offers a cost effective, sustainable, and ecologically friendly approach, particularly suitable for resource limited smallholder farmers [53], [54].

5.1. Comparison Between Modification Structures

Microclimate modification methods, broadly categorised into protected cultivation and vegetative approaches, differ substantially in their mechanisms, costs, and socio-ecological implications [11], [55]. Rather than re-state the categorical advantages of each, this section organises the available evidence around three analytical questions: (i) what measurable microclimatic buffering does each approach provide, (ii) under which crop and climate combinations is that buffering demonstrably effective against heat-driven biotic stress, and (iii) how robust is the underlying evidence base.

Quantitative heat-buffering performance

The most defensible quantitative claims concern closed environment protected cultivation in greenhouse and screen house systems. Air temperature reductions of 1.6–6.7 °C have been measured beneath 35–49 % photo-selective shade nets in tomato in India and Mediterranean Europe [56], [57], and maintaining the greenhouse vapour pressure deficit near the optimum of ~0.8 kPa and relative humidity at 50–70 % has been shown to increase hourly water uptake by 35–50 % relative to unmanaged regimes and to enhance tomato pollination around 60 % RH [49]. Such figures, however, are specific to well managed, sensor equipped structures. Under passive, naturally ventilated net covered greenhouses, internal and external air temperatures often remain nearly identical, and insect proof screens chiefly modify radiation and wind-driven vapour exchange rather than temperature itself [50].

Quantitative evidence is more heterogeneous and partly contradictory. A recent temperate-alley-cropping systematic review of n = 20 light-intensity, n = 10 air-temperature and n = 5 relative-humidity studies reported a consistent reduction in photosynthetically active radiation of 10–25 % close to tree rows and up to 42 % in dense red-oak systems, but found contradictory direction of effect for soil moisture, air temperature and VPD [11]. Only about half of the reviewed air-temperature studies showed the expected daytime cooling; Kanzler et al. observed the temperature buffer only within the poplar tree strips and not in the central crop alleys, and Swieter et al. measured higher afternoon air temperatures in alleys than in the open field, attributing this to reduced wind-speed limiting convective and latent heat transfer [11]. The most defensible heat-stress mitigation figures for temperate agroforestry are reductions in atmospheric water-stress VPD (>2.0 kPa) occurring 36 % less frequently and minimum RH being 19 % higher than in sole-cropping controls, indicating genuine buffering of evaporative demand during heat waves [11]. A tropical tree-based analogue is the cabruca cocoa system in southern Bahia: shade-tree canopy provides a documented shield against drought and high-temperature stress, yet even this system hit hard physiological limits during the 2015–16 ENSO, when a single drought event caused ~80 % yield loss and 11 % cocoa-tree mortality on surveyed farms [58], [59]. The strongest evidence for mitigating heat-driven biotic stress comes from 'push-pull' intercropping in eastern Africa. In this system, Desmodium intercrops repel pests like Chilo, Busseola, and Spodoptera frugiperda while attracting parasitoids, and suppress the parasitic weed Striga via suicidal germination; surrounding Napier or Brachiaria grasses function as trap crops [60]. Updated "climate-smart" versions using heat-tolerant companions highlight a critical trade-off: under heat, these companion plants can inadvertently become pest hosts [60]. Cabruca cocoa agroforestry provides similar resilience, buffering against heat and drought while enabling biological control of pests (such as capsids and mistletoe) that dominate unshaded monocultures. This approach also functions as economic insurance, allowing farmers to reduce labor and chemical inputs during stressful years without sacrificing their cocoa stock [58], [61].

5.2. Benefits of Microclimate Modification Structures in Agriculture

5.2.1 Agronomic benefits

Heat-stress alleviation is the most rigorously demonstrated benefit for closed-environment protected cultivation. Controlled greenhouse tomato experiments show that maintaining VPD near the optimum (~0.8 kPa) and RH at 50–70 % raised hourly water uptake by 35–50 % relative to unmanaged regimes and improved pollination around 60 % RH [49]; field-scale canopy-temperature reductions of 1.6–6.7 °C under 30–49 % shade nets provide the empirical basis for recommending shade nets during the warmest months in vegetables [56], [57]. Gap: the same effect is not consistently seen under low-tech screen-houses where internal and external air temperatures track each other closely [50], so generalising greenhouse VPD/RH recommendations to smallholder net houses is unwarranted.

Yield and quality gains are well evidence-based for high-value horticultural crops: ~50 % marketable-yield increase and a comparable reduction in fruit cracking under shade-grown tomato in Greece [57]; higher fruit weight, plant height and per-plant yield in shade-net vegetables across seasons in Tamil Nadu [62]. For vegetative modification, the strongest field evidence comes from temperate alley cropping, where Blanchet et al. demonstrated that pea yield was less drought sensitive in the agroforestry system than in sole cropping during an early spring drought (cited in [11]). Large-scale, multi-location quantitative yield data under combined heat and pest pressure remain scarce for cereals and pulses under agroforestry [11], [47].

Reproductive stage protection claims are largely extrapolated from heat stress physiology [27], [34] rather than directly tested in heat-stressed, pest-burdened field plots. Where orchardists shifted flowering dates to avoid early-season heat peaks in Uttarakhand, the linkage is observational rather than controlled [46]. There are very few field studies separate the microclimate effect on pollen viability from concurrent effects on pollinator activity and vector pressure during heat events.

5.2.2 Ecological benefits

Biodiversity and natural pest control are documented, but with substantial heterogeneity between earlier and more recent work. Although earlier single site studies reported inconsistent biological control responses to non-crop habitat (Karp et al., as cited in [63]), a multi year, multi region meta analysis suggests that composition effects on microclimate, arthropods and plant performance are more consistent across years and regions than previously assumed [55]. Even this meta analysis, however, notes that microclimate is itself a far less frequent covariate than ecological variables in landscape scale, pest control experiments [63].

Soil and carbon co-benefits are robustly demonstrated for vegetative modification but rarely coupled to pest outcomes under heat. Cabruca-style cocoa agroforestry in southern Bahia stores roughly two-thirds of regional above-ground carbon stocks and supports Atlantic Forest biodiversity on approximately 6,000 km² [64]; temperate alley-cropping systems reliably reduce surface runoff and improve infiltration once mature root systems establish [11].

Trade-offs that are too often obscured. Several frequently cited vegetative benefits carry offsetting costs. Increased humidity under dense canopies can exacerbate disease where the pathogen benefits from humidity more than the host benefits from cooling, many foliar fungi (e.g., grape powdery mildew at 22–28 °C [65], brown spot and sheath blight in rice at 25–30 °C [66], [67]) and bacterial wilts ([68], Table 1) all lie in moisture-friendly envelopes that dense canopies can favour. Shade induced spatial heterogeneity in temperature and humidity can produce uneven ripening [11] and uneven anthesis (e.g., earlier flowering near tree rows reported by Foereid et al. but delayed phenology near tree strips reported by Swieter et al., both in [11]).

5.2.3 Economic benefits

Capital amortisation and input substitution are the most consistently demonstrated economic advantages of protected cultivation, though they depend heavily on crop value per unit area. Mediterranean and high value Asian vegetable production has documented premium pricing and reduced agrochemical expenditure under shade nets and greenhouse systems [49], [50]; integrated pest management combined with protected cultivation in Jammu and Kashmir has reduced pesticide spending for several horticultural crops [46]. Life cycle assessments comparing cultivation systems in the Indian northern plains show that organic versus conventional field differences in global warming potential (904 vs. 1308 kg CO_2-eq ha^{-1}) are tractable, but protected cultivation is rarely included as a third axis, leaving its life cycle profile relative to open field and agroforestry systems under heat under quantified [69].

6.Summary and Suggestions for Further Study

Microclimate modification helps manage canopy temperature, soil moisture, humidity, and radiation at the crop and soil surface. These practices reduce heat stress, conserve soil moisture, limit excessive water loss and support more stable crop growth and yields. This review synthesizes current understanding of how elevated temperature influences crop microclimate, plant physiology, and biotic stress interactions, positioning microclimate modification as a key adaptation strategy.

Both protected cultivation structures and vegetative modification structures show strong potential to buffer thermal stress, stabilize humidity, reduce pest and disease pressure, and improve yield resilience across cereals, pulses, and vegetable cropping systems.

Future thrust on microclimate modification for crop health focuses on integrating traditional techniques with advanced technology and data analytics to mitigate the increasing risks from extreme weather events (e.g., heat waves, droughts, floods, and frost) driven by climate change. The proposed strategy aims to enhance agricultural resilience and ensure food security.

A potential area of interest for further work would be the development of low cost, farmer friendly, multi-pronged solutions that integrates the use of microclimate modification with integrated methods of addressing pests and diseases. In order to continue generating agriculture production, farmers' resilience and enhancing food security in the coming climate change, it is necessary to consider these and equip manipulation of microclimate to become a core technical solution. Additionally, future research must prioritize interdisciplinary approaches that align genetic improvement of heat-resistant cultivars with site-specific agronomic management and robust climate-smart training programs.

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