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Unveiling the impact of climate change on underutilized fruit crops: A review

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Abstract
Climate change profoundly impacts underutilized fruit crops, altering critical phenological stages (flowering, fruiting, ripening) and affecting yield, quality, and nutrition. Extreme weather events exacerbate risks (water stress, pests, diseases). Despite challenges, these crops exhibit genetic diversity and resilience. Innovative breeding (marker-assisted selection, genomic editing) can develop climate-resilient varieties. Sustainable practices (agroforestry, conservation tillage, integrated pest management) enhance resilience. Empowering local communities and conserving genetic resources unlock opportunities for nutritional security and livelihood enhancement.

Keywords: Indian plum, phalsa, neglected fruits, fruit diversity, crop production

Introduction
Climate change is fundamentally altering the environmental conditions on which agriculture depends, posing unprecedented challenges to global food security, biodiversity conservation, and sustainable development. Among various agricultural sectors affected, the cultivation and conservation of underutilized fruit crops stand out as a particularly vulnerable domain. Underutilized fruit crops, characterized by their marginal commercialization and limited global recognition, often serve as reservoirs of genetic diversity, cultural heritage, and traditional knowledge. Despite their intrinsic value, these crops have historically received inadequate attention in mainstream agricultural research and policy discourse (Ortiz *et al*., 2021) [44]. Underutilized fruit crops encompass a diverse array of plant species that have not received significant commercial attention or market demand compared to major commodity. Despite their marginal status in global agricultural systems, underutilized fruit crops possess unique attributes that make them valuable resources for food security, nutrition, and sustainable development. These crops are often characterized by their adaptation to specific agro-climatic conditions, resilience to pests and diseases, and nutritional richness (Singh *et al*., 2022) [41]. One of the distinguishing features of underutilized fruit crops is their genetic diversity, which often exceeds that of commercially dominant crops. This genetic variability not only contributes to the resilience of these crops to environmental stresses but also harbours potential traits for breeding climate-resilient varieties (Meena *et al*., 2022). In recent years, efforts have been made to prioritize the conservation and utilization of underutilized fruit crops as part of broader initiatives to promote agrobiodiversity, enhance food security, and build climate resilience. Initiatives such as participatory breeding programs, community-based conservation efforts, and value chain development projects aim to address the challenges facing underutilized fruit crops and unlock their potential for sustainable agriculture and rural development (Padulosi *et al*., 2011) [45].
Given these factors, the purpose of the study is to provide a comprehensive assessment of climate change's influence on underutilized fruit crops. We aim to understand the complex linkages between climate change drivers, biophysical responses, and socioeconomic repercussions in underutilized fruit crop production systems by combining empirical evidence, case studies, and expert insights. Through this comprehensive approach, we want to create practical research and policy suggestions to improve the resilience, sustainability, and equitable development of underutilized fruit crop systems in the face of climate change.

Diversity and distribution of underutilised fruit crop

Underutilized fruit crops exhibit remarkable diversity in terms of species, varieties, and genetic traits, representing a valuable but often overlooked component of global agricultural biodiversity (Li *et al*., 2020) [37]. These crops encompass a wide range of botanical families, including but not limited to Solanaceae, Myrtaceae, and Sapotaceae, each contributing unique flavors, textures, and nutritional profiles to the global food landscape. The distribution of underutilized fruit crops spans diverse agro-climatic regions, from tropical rainforests to arid deserts, reflecting their ability to adapt to varied environmental conditions. While some underutilized fruit crops are cultivated on a small scale in specific geographic regions, others remain largely wild or semi-wild, awaiting exploration and domestication. This diversity and distribution of underutilized fruit crops are crucial for enhancing agricultural resilience, preserving genetic resources, and promoting dietary diversity (Singh *et al*., 2022) [41].

Table 1: Names of different underutilised fruit crop and their characteristic

Fruit crop	Scientific name	Characteristics	Importance	Reference
Wood Apple	*Limonia acidissima*	Hard, woody fruit with aromatic pulp	Traditional medicinal uses; culinary applications	Kerkar *et al*., 2020 [31]
Indian Gooseberry	*Phyllanthus emblica*	Small, green fruit with sour taste	Rich in vitamin C; used in Ayurvedic medicine	Kulkami and Ghurghure, 2018 [33]
Karonda	*Carissa carandas*	Small, red or black berries with tart flavor	Edible fruit; medicinal uses	Rafique *et al*., 2023 [47]
Kokum	*Garcinia indica*	Small, purple fruit with sour taste	Culinary uses; refreshing beverage ingredient	Chate *et al*., 2019 [13]
Phalsa	*Grewia asiatica*	Small, purple berries with sweet-tart flavor	Nutrient-rich; potential for commercial cultivation	Kaur *et al*., 2024 [30]
Indian Hog Plum	*Spondias pinnata*	Oval-shaped fruit with tangy taste	Edible fruit; traditional medicine	Mondal *et al*., 2021 [43]
Ceylon Olive	*Elaeocarpus serratus*	Small, olive-like fruit with a bitter taste	Edible fruit; religious significance	Sudradjat and Timotius, 2022 [59]
Bilimbi	*Averrhoa bilimbi*	Small, green fruit with sour taste	Culinary uses; medicinal properties	Alhassan and Ahmed, 2016 [1]
Indian plum	*Flacourtia indica*	Small, purple-black berries with sweet-tart flavor	Edible fruit; potential for processing industries	Chandra *et al*., 2023 [12]
Wild jamun	*Syzygium cumini*	Small, purple-black berries with sweet-sour taste	Culinary uses; traditional medicine	Shrikant *et al*., 2012 [53]
Bael	*Aegle marmelos*	Round, hard fruit with aromatic pulp	Medicinal uses; traditional beverage ingredient	Sharma *et al*., 2022 [52]
Indian fig	*Ficus racemosa*	Small, purple fruit with sweet taste	Edible fruit; medicinal properties	Bhalerao *et al*., 2014 [6]
Star gooseberry	*Phyllanthus acidus*	Small, green fruit with sour taste	Culinary uses; medicinal properties	Brooks *et al*., 2020 [9]
Indian barberry	*Berberis aristata*	Small, red berries with tart taste	Medicinal uses; culinary applications	Moin *et al*., 2023 [42]

Nutritional importance

In terms of their nutritional qualities, most underutilized crops are superior. They are acknowledged for having higher-quality protein sources with enhanced essential amino acids and richer supplies of dietary fiber and carbohydrates (Sushree *et al*., 2021) [60]. The fruits are cheap and nutritious and known for medicinal and therapeutic properties. Many of the fruits, seeds and leaves are used as curative foods in traditional Indian medicine and Ayurveda. For example, bael fruit for beating the heat, ber being highly rich in vitamin C used in cases of Vit C deficiency (Vino *et al*., 2016) [61].

Characteristics and potential of underutilized fruit crops

The most frequent yield-limiting causes in the world are abiotic stresses brought on by environmental conditions; in important fruit crops, these stresses can account for up to 70% of production losses (Mantri *et al*., 2012; Zörb *et al*., 2019) [40, 62]. More specifically, the individual potential yield losses caused by the various meteorological adversities were reported as high temperature 40-50%, salinity 20%, drought 17%, low temperature 15% (Ashraf and Harris, 2005) [5]. Arid and semi-arid environments are thought to be hotspots for abiotic stresses such as severe temperatures, intense solar radiation, salt, drought, and nutrient deficiencies, causing commercial fruit crops to fail to grow or perform to their full potential. Under such climatic conditions, incorporating arid-zone underutilized fruit crops may be a more effective strategy for maintaining crop productivity under stress due to their typical morphological, physiological, anatomical, and biochemical xerophytic characteristics that allow them to perform optimally in harsh climates. Thus, adaptive features do not always result in a yield penalty. Examples of such traits include those that promote general resilience and resistance to suboptimal environmental conditions. Adaptive characteristics, which are normally assessed in terms of fertility, fruits, and seeds, are thought to ensure production stability under conditions. These traits, for example, can be phenology shifts (flowering/ripening at a particular time of year) or morphological traits (root/shoot ratio, leaf macro-and/or micro-morphological traits, *etc*.) that enable genotypes to withstand environmental stresses (which need not always involve an active and metabolically expensive stress response). This may lead to these genotypes' ability to produce ripening fruits in comparison to those lacking any adaptive characteristic (Meena *et al*., 2022) [41].

Table 2: Impact of climate on the phenology of underutilized fruit crops

Crop	Physiological disorder	Climatic factor	Impact	Reference
Wood apple	Blossom-end rot	Excessive rainfall	Increased susceptibility to fungal diseases, affecting fruit quality	Holthusen and Weber, 2021 [21]
Indian gooseberry	Sunburn	High temperatures	Damage to fruit skin, leading to reduced quality and yield	Singh *et al*., 2019 [57]
Kokum	Fruit cracking	Fluctuations in humidity	Cracks on fruit surface, increasing susceptibility to pathogens	Kaur *et al*., 2022 [29]
Karonda	Tip burn	Water stress	Browning and necrosis of leaf tips, affecting plant health	Hameed *et al*., 2021 [19]
Phalsa	Berry splitting	Erratic rainfall	Cracks on fruit surface, reducing market value and shelf-life	Kaur *et al*., 2024 [30]
Indian plum	Fruit drop	Heat stress	Premature shedding of fruits, leading to yield losses	Sharma, 2020 [26]
Ceylon olive	Leaf scorch	Drought	Wilting and drying of leaves, impacting tree health	Brito *et al*., 2019 [8]
Bael	Fruit abscission	Waterlogging	Premature dropping of fruits, reducing overall yield	Devlal *et al*., 2022 [14]
Indian barberry	Powdery mildew	High humidity	Fungal infection on leaves and fruits, affecting plant growth	Kalmarzi *et al*., 2019 [27]
Star gooseberry	Leaf spot	Excessive moisture	Lesions on leaves, reducing photosynthesis and plant vigor	Kamble *et al*., 2024 [28]
Indian hog plum	Fruit drop	Heat stress	Premature shedding of fruits, leading to yield losses	Mondal *et al*., 2021 [43]
Indian fig	Fruit rot	Prolonged rainfall	Decay of fruits, reducing marketability and shelf-life	Ammar *et al*., 2023 [4]
Bilimbi	Fruit splitting	Erratic rainfall	Cracks on fruit surface, reducing market value and shelf-life	Alhassan and Ahmed 2016 [1]

Climate change impact on fruit crop

Temperature

Heat stress

High temperatures can have detrimental effects on the growth and development of minor fruit crops. Heat stress (fig. 1) can lead to decreased photosynthesis, reduced flower and fruit set, and impaired fruit quality. Studies on minor fruit crops such as jujube (*Ziziphus mauritiana*) have shown that exposure to high temperatures during flowering and fruit development stages results in poor fruit set and reduced yields (Ishtiaq *et al*., 2016) [24].

Cold Stress

Extreme cold events, particularly frost and freezing temperatures, pose significant challenges to minor fruit crops (Lamichhane, 2021) [35]. Cold stress can damage tender plant tissues, leading to bud and shoot damage, reduced fruit set, and crop losses. Research on minor fruit crops like loquat (*Eriobotrya japonica*) has demonstrated that frost injury during winter months results in significant yield losses and affects fruit quality (Dhiman *et al*., 2022) [16].

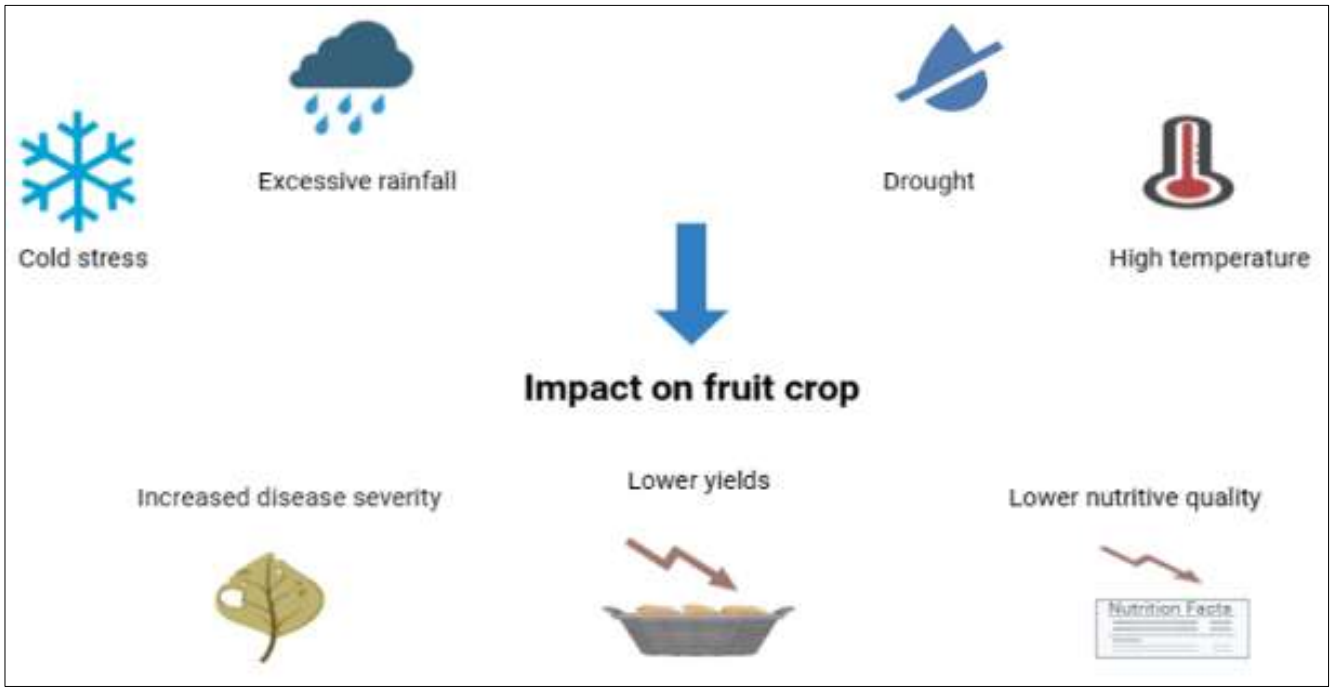

Fig 1: Impact of climate on fruit crop

Precipitation Changes

Drought Stress

Erratic rainfall patterns and prolonged drought conditions induce drought stress in minor fruit crops, leading to water scarcity and reduced plant growth. Drought stress results in wilting, leaf senescence, and decreased fruit yield (Farooq *et al*., 2009) [18] Research on minor fruit crops such as Indian gooseberry (*Phyllanthus emblica*) has highlighted the adverse effects of drought stress on fruit development, leading to reduced fruit size and increased fruit drop (Pandey *et al*., 2019) [46].

Excessive Rainfall

Conversely, excessive rainfall and poor drainage can cause waterlogging, leading to oxygen deprivation in the root zone and subsequent root rot. Waterlogged conditions reduce nutrient uptake and impair plant growth, ultimately affecting fruit yield and quality (Kim *et al*., 2024 [32]. Studies on minor fruit crops like Indian hog plum (*Spondias pinnata*) have shown that waterlogging leads to decreased tree vigor, poor fruit quality, and increased susceptibility to diseases (Dey *et al*., 2016) [15].

Water availability

Optimal Irrigation

Adequate water supply through efficient irrigation management is essential for maintaining optimal growth and productivity of minor fruit crops. Proper irrigation scheduling based on crop water requirements helps mitigate the adverse effects of water stress and improve fruit yield and quality (Bwambale *et al*., 2022) [11]. Research on minor fruit crops such as phalsa (*Grewia asiatica*) cultivation has demonstrated the importance of optimal irrigation practices in enhancing fruit yield and quality (Singh *et al*., 2020) [54].

Impacts of climate change underutilized fruit crops production

Production of fruits

Climate change can exert significant impacts on the yield of underutilized fruit crops through multiple pathways. Changes in temperature regimes, including increases in average temperatures and occurrences of heatwaves, can disrupt critical developmental stages such as flowering, fruit set, and maturation. High temperatures during flowering can lead to flower abortion and reduced pollination success, resulting in diminished fruit set and ultimately reduced yields (Saqib *et al*., 2022) [49]. Conversely, warmer temperatures may accelerate fruit ripening, shortening the fruiting period and reducing the overall yield potential. Erratic precipitation patterns associated with climate change, such as droughts or heavy rainfall events, can exacerbate water stress and affect fruit development. Drought conditions can impair water uptake and nutrient absorption, leading to reduced growth and yield. On the other hand, excessive rainfall can cause waterlogging, root damage, and nutrient leaching, further compromising yield (Lesk *et al*., 2022) [36]. Extreme weather events, including storms, hailstorms, and cyclones, can cause physical damage to crops, resulting in yield losses. Hailstorms can bruise or puncture fruits, reducing their market value and shelf life. Frost events can damage tender plant tissues, affecting future growth and yield potential. These extreme events pose significant challenges to underutilized fruit crop production, especially for smallholder farmers in vulnerable regions (Seneviratne *et al*., 2021) [50].

Productivity of fruits

Climate change can also impact the overall productivity of underutilized fruit crops by altering the duration and intensity of the growing season, as well as the frequency and severity of pest and disease outbreaks. Changes in temperature regimes influence the timing of phenological stages, such as bud break, flowering, and fruit maturation, thereby affecting the duration of the growing season (Howden *et al*., 2007) [22]. Shifts in temperature and moisture regimes can also influence the incidence and severity of pest and disease pressures, further affecting crop productivity. Elevated temperatures can accelerate physiological processes in plants, leading to earlier bud break and flowering. While this may initially extend the growing season and enhance productivity, it can also increase the risk of heat stress during critical growth stages, leading to yield losses (Bradford *et al*., 2019) [7]. Changes in precipitation patterns can disrupt irrigation schedules and soil moisture levels, affecting plant water uptake and nutrient availability. Water stress conditions during key growth stages can lead to reduced plant vigor, smaller fruit size, and poor fruit quality, ultimately impacting productivity. Increased pest and disease pressures, driven by warmer temperatures and altered humidity levels, can further compromise crop productivity. Pests such as insects, mites, and pathogens thrive under favorable climatic conditions, leading to outbreaks that can cause significant damage to underutilized fruit crops (Dudenhöffer *et al*., 2022) [17].

Quality of fruits

Climate change can influence the quality attributes of underutilized fruit crops, including flavor, texture, color, and nutritional content. Changes in temperature regimes and precipitation patterns can alter the biochemical composition of fruits, affecting flavor development, sugar accumulation, and acid content. Warmer temperatures can accelerate fruit ripening and soften fruit tissues, leading to changes in texture and pulp consistency (Ameen *et al*., 2023) [3]. Water stress conditions can also reduce fruit size, juice content, and overall quality. Changes in climatic conditions can also affect the concentration of secondary metabolites and phytochemicals in fruits, influencing their antioxidant properties and nutritional value. Elevated temperatures and prolonged heatwaves can lead to increased oxidative stress in plants, triggering the production of antioxidants as a defense mechanism (Lisar *et al*., 2012) [38]. However, prolonged exposure to high temperatures can also degrade heat-sensitive compounds such as vitamin C and anthocyanins, reducing the nutritional quality of fruits. Water stress conditions can further exacerbate nutrient deficiencies and impact fruit quality. Reduced water availability can impair nutrient uptake and translocation within the plant, leading to imbalances in nutrient concentrations and suboptimal fruit development (Zhao *et al*., 2020) [63].

Adaptation strategies to enhancing the resilience of underutilized fruit crop

Diversification of crop varieties

Expanding the genetic diversity within underutilized fruit crop species can enhance resilience to climate change. This involves identifying and promoting varieties that are better suited to changing climate conditions, such as those with drought or disease resistance (Jain *et al*., 2023) [26].

Agroforestry and intercropping
Integrating underutilized fruit crops into agroforestry systems or intercropping arrangements can provide multiple benefits. Agroforestry systems offer increased resilience by providing shade, improving soil health, and reducing water stress. Intercropping can also enhance biodiversity and provide additional income streams (Burgess *et al*., 2022) [10].

Water management
Improved water management practices, such as rainwater harvesting, drip irrigation, and efficient water use technologies, can help mitigate the impacts of climate change-induced droughts and water scarcity on underutilized fruit crops (Kumar *et al*., 2023) [34].

Soil health management
Maintaining soil health through practices like cover cropping, composting, and reduced tillage helps improve the resilience of underutilized fruit crop systems to climate change impacts, such as soil erosion, nutrient depletion, and changes in soil structure (Indira *et al*., 2023) [23].

Pest and disease management
Climate change may exacerbate pest and disease pressures on underutilized fruit crops. Integrated pest management (IPM) strategies, including biological control, crop rotation, and resistant varieties, can help minimize losses and enhance resilience (Subedi *et al*., 2023) [58].

Capacity building and knowledge sharing
Providing training and extension services to farmers on climate-smart agricultural practices tailored to underutilized fruit crops is crucial. This includes educating farmers on climate-resilient techniques and facilitating knowledge sharing among stakeholders (Raj and Garlapati, 2020) [48].

Conclusion
The impact of climate change on underutilized fruit crops presents a complex and multifaceted challenge with significant implications for global food security, biodiversity conservation, and livelihood sustainability. This analysis has underscored the diverse ways in which climate change affects underutilized fruit crops, from altering phenological stages to exacerbating water stress and susceptibility to pests and diseases. The findings highlight the urgent need for proactive measures to enhance the resilience of underutilized fruit crop systems in the face of climate variability. While climate change poses formidable threats to underutilized fruit crops, it also presents opportunities for innovation and adaptation. Additionally, efforts to conserve and valorise underutilized fruit crop genetic resources are essential for preserving biodiversity and harnessing the adaptive capacity of these crops. Addressing the impact of climate change on underutilized fruit crops requires a holistic and collaborative approach that engages stakeholders across sectors and scales. By integrating climate resilience into agricultural policies, promoting research and development initiatives, and fostering knowledge-sharing networks, we can build more resilient food systems and safeguard the future of underutilized fruit crops. Ultimately, investing in climate-smart strategies for underutilized fruit crop cultivation is not only essential for adapting to climate change but also for ensuring the long-term sustainability and resilience of agricultural systems worldwide.

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