



Southern African Journal of Communication and Information Science

Special Issue: Climate Change

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To cite this article: Zanamwe, P., Tembo, L., Mbiza, N. I. T., Tshuma, E. M., and Mbiza, J. 2026. Shifting from Annual Crops to Fruit Production as a Climate Change Adaptation Strategy: Opportunities and Dilemmas. *Southern African Journal of Communication and Information Science*. 4(1): 50-72

Published Online: 21 August 2026

SAJCIS

2026, Vol. 4, No. 1, 50-72.

Shifting from Annual Crops to Fruit Production as a Climate Change Adaptation Strategy: Opportunities and Dilemmas

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Abstract

The purpose of this study was to examine the possibility of shifting from annual crop production to fruit tree cultivation as a climate change adaptation strategy. Annual crop farmers are increasingly shifting to fruit tree production as a climate change adaptation strategy. Compared to annual crops, fruit trees are generally more resilient to weather extremes. However, fruit production is also vulnerable to the impacts of climate change. Unlike annual crops, fruit trees remain in orchards for many years, limiting the applicability of some adaptation methods such as altering planting dates. The study employed a literature review and meta-data analysis to examine effects of climate change on fruit physiology and climate change adaptation strategies under changing climatic conditions. Frequently identified strategies included planting climate-resilient fruit tree varieties, relocating production sites, adopting climate-smart practices and strengthening pest management. Additional strategies including crop insurance and stronger institutional support systems were also highlighted. A conceptual model to guide farmers transitioning from field crops to fruit tree production that benefit researchers, policymakers, extension officers and other agricultural stakeholders was developed. The study provides a framework for transitioning from annual crop production to fruit tree cultivation as a climate change adaption strategy, highlighting the comparative resilience of fruit trees to certain climate-related hazards, while acknowledging the vulnerabilities associated with orchard production.

Keywords: *Climate change adaptation; extreme weather events; climate-resilient fruit varieties; shifting production zones; new fruit farmers.*

Introduction

Climate change refers to long-term shift in climate patterns, driven by both natural processes and human activities, which persist for decades (Duteil, 2024). These shifts include rising global temperatures, increased atmospheric carbon dioxide (CO₂) concentrations, altered rainfall patterns and more frequent weather events (Rajan *et al.*, 2020; Manzoor *et al.*, 2024). Such changes affect various sources of human livelihoods, with agriculture being particularly vulnerable due to its strong dependence on climatic factors (Grigorieva *et al.*, 2023). As agriculture underpins food and nutrition security, the impact of climate change on the sector has direct consequences on human well-being. To safeguard production systems, a variety of mitigation and adaptation strategies have been introduced, aiming to reduce risks and build resilience (Williams *et al.*, 2021). Adaptation, in particular, seeks to minimize the risks posed by climate change while capitalizing on potential opportunities (Vuković Vimić *et al.*, 2023).

One adaptation pathway that is gaining traction is the shift by farmers from annual crop production to fruit tree cultivation. Compared to annual crops, fruit trees are generally more resilient to climatic extremes such as floods, drought, heat waves and hailstorms. Even when exposed to such stressors, they often produce a harvestable crop, although with reduced yield and quality. Importantly, fruit trees contribute to carbon sequestration, capturing atmospheric carbon dioxide and storing it in trunks, foliage, branches and roots (Hardaker, Bodner and Dandy, 2022). This dual role positions fruit production as both an adaptation and mitigation strategy. Therefore, farmers benefit from consumption and marketing of fruits, as well as in carbon financing.

Nevertheless, fruit tree cultivation is not without challenges. Climate change introduces multiple physiological stresses that compromise yield stability and fruit quality (Ahmed and Stepp, 2016). Trees respond to abiotic stress through integrated physiological mechanisms such as ion homeostasis, osmolyte synthesis, antioxidant regulation and morphological adjustments (reduced organ size, leaf abscission, and restricted root growth) (Abobatta, 2021a). While these mechanisms help trees survive, they also alter growth processes and negatively affect productivity (Karagatiya *et al.*, 2023). Rising temperatures, for example, may accelerate flowering, thereby exposing blossoms to spring frost (Chawla *et al.*, 2021). Heat stress also affect fruit colour development on apples (*Malus domestica*) and grapes (*Vitis vinifera*), and peel puffing in satsuma mandarin (*Citrus*

unshiu). Similarly, inadequate chilling hours in temperate fruits reduce yields, as seen in Japanese pear (*Pyrus pyrifolia*), where disrupted dormancy increased frost damage risk (Ramírez and Kallarackal, 2015; Sugiura *et al.*, 2019).

Given the economic and nutritional importance of fruits, addressing threats posed by climate change is critical to sustaining fruit production. According to Rajatiya (2018), the design and implementation of robust adaptation measures can significantly reduce these impacts. Sugiura *et al.* (2019) proposed a three-step adaptation framework: (i) applying production technologies to existing orchards, (ii) replanting with climate tolerant cultivars and (iii) relocating fruit production to more suitable zones. Chawla *et al.* (2021) highlighted technological innovation, improved orchard management and cultivar development as central to sustaining productivity. Ameen *et al.* (2023) further identified a range of cultural and physiological strategies, including varietal selection, artificial defoliation, microclimate control, pigmentation management and phyto-hormonal regulation of dormancy. These findings illustrate that while fruit trees present opportunities for climate change adaptation, they also face significant vulnerabilities. This review therefore, examined the dilemma of shifting from annual crop production to fruit tree cultivation as an adaptation strategy. Specifically, the objectives were to: (i) assess the principal impacts of climate change on fruit tree physiology and productivity (ii) identify suitable adaptation strategies for fruit farmers and (iii) propose a conceptual model to guide farmers transitioning from field crops to fruit tree production.

Methodology

The study employed a systematic review approach to synthesize evidence on the transition of farmers from annual crop production to fruit tree production as a climate change adaptation strategy. The review followed the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) framework, which provides a structured process for literature identification, selection and appraisal. Relevant studies were identified through comprehensive searches in leading academic databases, namely, AGORA, Scopus, Science Direct, and Google Scholar (Figure 1). The search strategy combined keywords and their synonyms to capture a wide range of relevant literature. Key search items included: “*climate change*,” “*climate adaptation*,” “*fruit culture*,” “*climate-resilient fruit production*,” and “*climate change mitigation in fruit culture*” The

search yielded an initial total of 220 articles.

Eligibility criteria were applied to ensure that included studies met the objectives of the review. Articles qualified for inclusion if they: (i) focused primarily on fruit production, (ii) examined climate change impacts or adaptation strategies, (iii) were peer-reviewed journal articles, and (iv) were published in English during the period 2000 to 2024. A two-stage screening process was implemented. The first stage involved title and abstract screening, while the second stage entailed a full-text review. Of the 220 retrieved, 18 duplicates were removed. A further 109 articles were excluded at the title or the abstract stage for not meeting the inclusion criteria. The remaining 93 articles underwent full-text assessment and 48 were excluded for lacking a focus on fruit production or failing to address climate change impacts/adaptation strategies. Ultimately, 45 articles satisfied all inclusion criteria and were retained for in-depth analysis.

Figure 1 summarizes the article identification screening and selection process in accordance with the PRISMA framework.

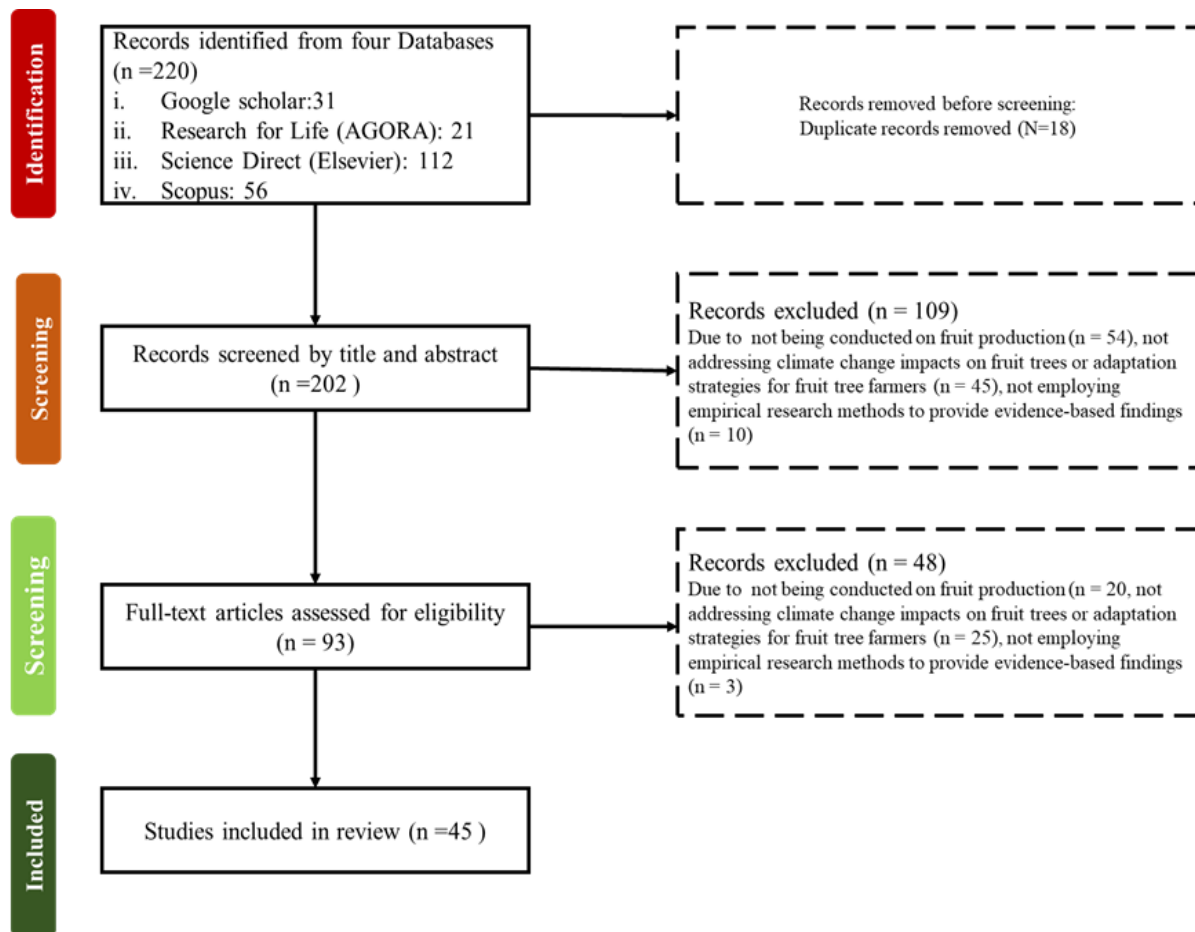


Figure 1: Systematic review according to the PRISMA Model

Data relevant to the study objectives were systematically extracted from full texts of the selected articles. Information on climatic factors affecting fruit production was compiled, with the documented impacts of climate change on fruit culture categorized into six major themes and the adaptation strategies in fruit culture were grouped into nine categories. In addition, farmer support mechanisms were also considered. The synthesized data informed the development of a decision support model designed to guide farmers shifting from annual crop production to fruit tree cultivation as a climate change adaptation strategy in making informed and sustainable choices under changing climatic conditions.

Results

Climatic factors affecting fruit production

Several climatic factors associated with climate change have been found to significantly affect fruit tree production. These include rising temperatures, increasing atmospheric carbon dioxide concentrations, rainfall variability and extreme weather events such as frost, heat waves, floods, cyclones, droughts, and hailstorms (Karagatiya *et al.*, 2023). Rising temperatures causes some temperate fruit production areas to fail to meet chilling requirements necessary for bud burst (Webb *et al.*, 2007), rendering certain areas unsuitable for pome fruit production (Thompson *et al.*, 2014). In citrus production, warmer than expected autumn and winter temperatures accelerated citrus flowering and subsequent drops in temperature post-flowering led to flower loss, reduced fertility and increased alternate bearing (Karamidehkordi *et al.*, 2023).

Elevated carbon dioxide levels also influence fruit tree yield and quality. Higher concentrations of carbon dioxide accelerate tree development, thereby increasing demand for irrigation (Rajatiya, 2018). Additionally, insect pests such as aphids and weevil larvae proliferated in response to elevated carbon dioxide (Karagatiya *et al.*, 2023). A combined rise in carbon dioxide and temperature reduced strawberry yields by decreasing both the number of inflorescences and the size of umbels (Rajatiya, 2018). Rainfall variability also pose major challenges to fruit production. Karamidehkordi *et al.* (2023) noted that shifts in rainfall patterns, combined with rising temperatures, lead to droughts, declining water tables and increased salinity, all of which reduce fruit yields. Rainfall during the flowering season wash pollens from the stigma, resulting in poor or failed fruit set (Chawla *et al.* (2021). Moreover, prolonged cloud cover and associated high humidity increase disease incidence (Karagatiya *et al.*, 2023), while low humidity adversely affects fruit set due to poor pollen germination caused by desiccation of stigmatic fluid (Rajan *et al.*, 2020).

Extreme weather events such as heat waves, droughts, hailstorms and frost also cause severe damage to fruit trees, reducing both yield and quality (Chaurasia *et al.*, 2023). In *Litchi chinensis*, drought conditions have been linked to reduced fruit set and increased fruit cracking (Mitra, 2018). Hailstorms damage fruit trees and young fruits, with direct consequences to fruit yield and quality (Haque *et al.*, 2024). A combination of drought and high temperatures often results in heat waves that cause flower and fruit abortion, ultimately lowering yields and reducing fruit quality (Abobatta, 2021a). Specific examples include flower drop in female and hermaphrodite papaya (*Carica papaya*) (Rajan *et al.*, 2020) and scorching of leaves and twig dieback in mango (*Mangifera Indica*) (Chawla *et al.*, 2021). Hot, humid conditions also promote pests and diseases

such as fruit fly (*Psidium guajava*) in guava and leaf curl virus in papaya (Chawla et al., 2021). Heat waves further reduce fruit quality by increasing sugar concentration while decreasing acidity (Sasmoko et al., 2022). Intense storms and hailstorms physically damage fruit trees and bearing branches, weakening them and increasing vulnerability to pests and diseases. (Abasi et al., 2025). Frost is particularly damaging during the flowering stage, leading to flower drop (Abasi et al., 2025). Frost also slows fruit development and disrupts pollination, thereby reducing yields. Floods increase soil salinity, which negatively affects fruit productivity in crops such as citrus, grapes (*Vitis vinifera*) and mango (*Mangifera indica*) (Kumar, 2024). In grapes, increased salinization reduces vine growth, photosynthesis, yield, and fruit quality (Keller, 2010).

Effects of climate change on fruit production

Several effects of climate change on fruit production have been identified, including reduced yield, declining fruit quality, increased pest incidences, phenological changes and insufficient chilling hours.

Reduction of fruit tree yield

Reduced fruit yield is the major impact of climate change on fruit production. Asare-Nuamah et al. (2022) observed that recurring droughts, rising temperatures, declining rainfall, and increased pest outbreaks significantly reduced mango yields. Rahimzadeh (2017) noted similarly low apple yields in Indiana Himalaya. In citrus production, Karamidehkordi et al. (2023) linked declining yields to drought, extreme cold and salinity. In Gujarat, India, unseasonal rainfall followed by heavy dew during mango flowering caused poor fruit set, pea-stage fruit drop and higher incidences of sooty mould and powdery mildew, resulting in yield losses of up to 80 - 90 % (Rajatiya, 2018; Karagatiya et al., 2023). Chawla et al. (2021) highlighted that shorter growing periods caused by terminal heat stress and limited water suppressed fruit production. In grapes, insufficient winter chilling reduced yield due to delayed budburst, reduced bunch numbers and inconsistent fruit development (Webb et al., 2007). For olive trees, temperature extremes and water stress limited fruit growth and output (Moriondo, Stefanini and Bindi, 2008). In strawberries, elevated CO₂ and higher temperatures reduced fruit yields. Collectively, these findings confirm that floods, drought, pests, extreme temperatures, variable rainfall and elevated CO₂ have significant negative impacts on fruit tree yield

Fruit quality

Climate change affects fruit quality, thereby influencing marketability. Haque *et al.* (2024) noted that severe climatic conditions, including heat waves, floods, droughts and cyclones, downgraded the quality of tropical fruits such as pineapple, litch and mango. In temperate fruits, fluctuating temperatures can trigger physiological disorders such as bitter pit, cork spot, superficial scald, sunburn and sunscald (Chaurasia *et al.*, 2023). Rahimzadeh (2017) found that apple quality declined in lowland areas but improved in the upland areas of the Indian Himalaya, due to warming. In grapes, Keller (2010) observed that anthocyanin accumulation stops or degrades above 35°C, affecting fruit colour. Similarly, warm temperature result in higher sugar accumulation, lower acidity and hence, unbalanced wines (Webb *et al.*, 2007). In mangoes, strawberries and apples, elevated temperature increase total soluble solids, reduce acidity and produce insipid or dry fruits (Rajatiya, 2018). Modern apples were found to be softer and less sour compared to 40 years ago and this was attributed to higher pre-harvest temperatures that reduce firmness and acidity (Houston *et al.*, 2018). Again, prolonged heat exposure cause sunburn, water core and textural loss in apples. Furthermore, reduction of irrigation to 25 -50 % decreased fruit size in Gala apples (El Jaouhari *et al.*, 2018). In mango, high temperatures cause formation of spongy tissue (Karagatiya *et al.*, 2023). In citrus, freezing temperatures, frost, snow and hail reduced fruit storage life, caused bitterness, dehydration and skin damage (Karamidehkordi *et al.*, 2023).

Pests

Climate change directly affects insect biology influencing life cycles, reproduction, dormancy, movement, survival and genetic adaptation. Warmer springs accelerate reproduction, while high temperatures combined with humid atmosphere create optimal conditions for disease development. For mango, Mitra (2018) reported higher fruit fly incidences as temperatures rose from 20 to 35°C. Mango farmers in Ghana identified climate change as a driver of increased pests and disease problems (Asare-Nuamah *et al.* 2022). In Australia, floods increased pineapple and mango diseases (Haque *et al.*, 2024). In India, climate change accelerated emergence of insects and pollinators in temperate fruit-growing regions (Rahimzadeh, 2017). In citrus, rising incidences of insect pests and diseases have also been observed in Iran (Karamidehkordi *et al.*, 2023). Increased humidity also fuels higher mango hopper and powdery mildew infestations (Rajatiya,

2018; Rajan *et al.*, 2020).

Phenological changes

Phenology refers to fruit development stages such as budding, flowering, fruit set, ripening, and leaf fall. Climate change has altered these phenological patterns in several ways. Haque *et al.* (2024) observed disrupted maturity schedules in tropical fruits due to extreme weather. Higher temperatures advance flowering, increasing susceptibility to subsequent spring frosts (Abasi *et al.*, 2025). Rahimzadeh (2017) noted that reduced freeze periods in temperate regions led to earlier bud burst and blossom development. In mango, higher temperatures promoted vegetative growth, affecting flowering phenology (Karagatiya *et al.*, 2023). In grapes, warming accelerated annual growth cycles, leading to earlier flowering, veraison, and harvest (Keller, 2010). Again, early springs caused early budburst, increasing frost vulnerability (Houston *et al.*, 2018). In strawberry, low temperatures ($< 15.6^{\circ}\text{C}$) stalled flower differentiation and promoted vegetative growth (Neri *et al.*, 2012). These studies confirm that climate change disrupts fruit tree phenology through altered flowering, early budburst and changing the ripening patterns.

Insufficient chilling hours

The chilling requirement; the period of low-temperature exposure needed to break dormancy and ensure proper bud development; varies across fruit species and cultivars. Adequate chilling is essential for optimal bud development and subsequent growth phases (Abasi *et al.*, 2025). Climate change, especially the rising temperature, reduce accumulation of chilling units, leading to weak or inconsistent bud break, poor fruit development, smaller fruits and irregular ripening (Meza *et al.* (2023). In pome fruits, warm temperatures triggered premature dormancy breaking (Rajan *et al.*, 2020). In peach, plum and apricot warm winters delayed flowering (Tsvakirai and Mosikari, 2020; Borgini *et al.* 2024). In apples, Rahimzadeh (2017) reported insufficient chilling in previously favourable lowland areas in Indiana Himalaya. These studies indicate that rising temperature is the primary cause of insufficient chilling in temperate fruit trees, with widespread implications for production.

Climate adaptation strategies in fruit culture

The fruit industry has increasingly adopted a range of strategies to cope with the impacts of climate change. This review revealed several adaptation strategies commonly applied in fruit tree

production, including use of climate-smart varieties, careful site selection, use of climate resilient rootstocks and adoption of climate smart cultural practices. Other strategies identified are application of climate sensitive technologies, crop diversification, improved pest management, product diversification and leveraging available farmer support systems.

Genetics and resistant varieties

Planting climate-resilient fruit trees emerged as a key climate change adaptation strategy (Houston *et al.*, 2018). Rahimzadeh (2017) observed that replacing apple varieties in the Indiana Himalaya enabled farmers in warming lowland areas, where traditional cultivars were no longer suitable, to sustain production. For instance, improved apple varieties, such as *Fuji* and *Pink Lady*, which require only 200 - 400 chilling hours, can thrive in areas with increasingly warm winters that are unsuitable for conventional cultivars (Houston *et al.*, 2018). Likewise, high-chill cultivars such as *Royal Delicious* are being replaced by low chill cultivars in many production areas (Chawla *et al.*, 2021). In Norway, apple varieties, Gravensten and Sumerred have low heat requirements, hence, bloom early and varieties Aroma and Elstar bloom later due to higher heat requirements (Vuković Vimić *et al.*, 2023). Breeding programs are increasingly focused on developing new fruit tree types with traits such as low chill requirement, heat tolerance, drought-resistance and disease resistance (Chaurasia *et al.*, 2023). In peach and nectarine, cultivars requiring fewer than 400 chill hours produce good yields even during warming winters, as they flower and fruit reliably after short dormancy periods (Tsvakirai and Mosikari, 2020). Additionally, peaches and nectarine varieties with upright growth structures perform better under windy conditions than spreading types (Tsvakirai and Mosikari, 2020). In citrus production, reliance on susceptible cultivars have increased vulnerability. Karamidehkordi *et al.* (2023) found that although farmers in Iran prefer *Thomson Navel* oranges, this cultivar is more susceptible to cold stress than local varieties such as *Satsuma* mandarins which can be harvested earlier and thus escape frost damage. Choosing frost resistant cultivars therefore reduces frost risks. In grapes, the French National Institute of Origin and Quality, authorized six new grape varieties for Bordeaux wines due to their strong resilience to climate change impacts (Borghini, 2023). These studies suggest that climate-resilient varieties are already available for some crops, while breeding programs continue to expand options. Adoption of resistant cultivars, whether low-chill apples, cold-hardy citrus, wind tolerant peaches or resilient grape varieties represents a critical adaptation pathway for sustaining fruit production

under climate change.

Site/production location

Relocating fruit production from areas rendered unsuitable by climate change to new favorable locations has emerged as a key adaptation strategy. Meza *et al.* (2023) highlighted orchard relocation as an effective means of reducing climate related risks, while Rajan *et al.* (2020) emphasized that establishment of new production areas can mitigate the effects of extreme weather events. In a survey on the effects of climate change on tropical fruit cultivation in Australia, Haque *et al.* (2024) reported that choosing appropriate production environments serves as a long-term measure to minimize flood risks. Similarly, in the Indian Himalayas, Rahimzadeh (2017) observed a shift in apple production from lower elevations, which had become unsuitable, to higher altitudes with more favorable conditions. In Norway, Vuković Vimić *et al.* (2023) observed that the expansion of fruit cultivation into southern and eastern regions, as well as into parts of Western Norway was driven by climate-induced suitability. In North America, Houston *et al.* (2018) noted that new apple orchards are being established at higher elevations to reduce heat stress, while Webb, *et al.* (2007) reported that grape production can successfully expand into cooler zones. In India, Karagatiya *et al.* (2023) found that low-chill cultivars of apple, peach, and plum, enable commercial fruit cultivation in the lower hills and North Indian plains, areas previously unsuitable for these crops. Strategic site placement also plays a protective role against frost damage. Perennial crops planted on slopes less vulnerable to sudden temperature drops offer natural protection to trees. Overall, these findings suggest that shifting production to climatically favorable areas whether through relocation and elevation shifts, represents a viable and widely practiced adaptation strategy under changing climatic conditions.

Grafting and resistant rootstocks

The use of stress-tolerant rootstocks in grafting is increasingly recognized as a means of enhancing the resilience of fruit trees to climate variability (Mitra, 2018; Karagatiya *et al.* 2023). Grafting fruit trees onto rootstocks known for tolerance to drought or extreme temperatures improve their overall resilience. Chaurasia *et al.* (2023) compiled a comprehensive list of cultivars which can make stress resistant rootstocks across different fruit species. Similarly, Abobatta (2021a) highlighted that rootstocks resistant to drought and salinity enhance the sustainability of the fruit

trees under climate change stresses. Kuznetsova et al. (2021) reported stress-resistant plum cultivars suitable as rootstocks, including ‘Stanley’, ‘Milena’, ‘Renklod’ and ‘Donetskiy-1’. Mitra (2018) observed that ‘Sharad Seedless’ grapes grafted on ‘Dogridge rootstock exhibited maximum water-use efficiency and sweet oranges grafted on ‘Cleopatra’ mandarin showed high water use efficiency under deficit irrigation. Grapevine rootstocks derived from *V. berlandieri* × *V. rupestris* and *V. berlandieri* × *V. riparia* demonstrated strong drought tolerance whereas rootstocks from *V. cinerea* and 3309C varieties showed notable flood tolerance (Mitra, 2018). Overall, these findings provide compelling evidence that selection of climate resilient rootstocks represent an effective adaptation strategy in fruit tree production.

Cultural practices

There is substantial evidence that fruit farmers are adopting diverse cultural practices to cope with climate change impacts. Nath et al. (2018), reported that climate smart cultural practices enhance productivity, while Borghini *et al.* (2023) identified reducing plant height, adjusting the leaf area to fruit weight ratio and pruning, as widely adopted adaptation strategy in grape production in Australia. Tree training also emerged as an important practice. Houston *et al.* (2018) observed that canopy training reduced fruit damage from heat stress by minimizing direct exposure to sunlight. Moisture management is another critical adaptation strategy. In Ghana, mango farmers employed irrigation alongside improved seedling management to mitigate drought risks (Asare-Nuamah *et al.* 2022). Surface irrigation and application of heat were found to minimize frost damage in citrus (Karamidehkordi et al., 2023).

A range of additional orchard practices further enhance resilience. Windbreaks provide critical protection against cyclones, safeguarding orchards from intensifying climate hazards (Abasi *et al.*, 2025). Integrated Pest Management (IPM) has also been recognized as effective in addressing increased pest pressure (Rajan *et al.*, 2020). Other innovative practices include increasing canopy albedo with white kaolin powder sprays to reduce heat stress (Meza *et al.* 2023).

Mulching stands out as a widely reported adaptation practice. It conserves soil moisture, making it particularly effective under low-moisture conditions (Thompson et al. 2014; Meza *et al.*, 2023). Applying organic or inorganic mulch forms a protective barrier that reduces evaporation and promotes water retention. Empirical evidence shows substantial yield gains from plastic mulching

in papaya (64.24 %), mango (45.23 %), banana (33.95 %), ber (27.06 %), guava (25.93 %), pineapple (14.63 %) and litchi (12.61 %) (Karagatiya *et al.*, 2023). In citrus, mulching improved fruit and inflorescence retention, fruit weight and fruit taste (Al-Qthanin *et al.* 2024). Mitra (2018) found that combining plastic mulch with drip irrigation significantly improved fruit quality and yield in citrus-growing areas of western Japan.

Technological advancement

Various technologies can be applied in fruit production strategies for adapting to changing climatic conditions. Abasi *et al.* (2025) noted that weather monitoring systems and predictive models enable farmers to take proactive measures in climate impacts. Similarly, soil moisture sensors provide real-time soil moisture data, facilitating efficient irrigation scheduling and reducing unnecessary water use (Chaurasia *et al.*, 2023). In Ghana, mango farmers adopted improved irrigation techniques to increase productivity under drought and erratic rainfall conditions (Asare-Nuamah *et al.*, 2022). Rajan *et al.* (2020) also reported the uptake of drip irrigation as a climate change adaptation measure. Haque *et al.* (2024) reported construction of dams as a vital strategy for adapting to prolonged droughts. Similarly, water recycling and harvesting techniques have also been reported to strengthen resilience in water-scarce environments (Rajan *et al.*, 2020). Other technologies include spraying fruit trees with anti-transpirants, such as chitosan, kaolin, and liquid paraffin, to reduce transpiration (Karamidehkordi *et al.*, 2023). For flooding, Abasi *et al.* (2025) reported that construction of drainage systems in orchards is effective in preventing waterlogging and its associated crop damage.

Innovative frost protection technologies are also emerging. Abasi *et al.*, (2025) highlighted the use of row covers and wind mixing machines. In Northwest America, Houston *et al.* (2018) reported the use of wind machines, stack heaters, and sprinkler irrigation to protect orchards against frost. In grapes, use of heaters and spraying with Bordeaux mixture were reported to mitigate frost damage under low temperatures (Rajan *et al.*, 2020; Karagatiya *et al.*, 2023). In citrus, Karamidehkordi *et al.* (2023) highlighted the use of antifreeze chemicals. Windbreaks have also been adopted to reduce frost and wind damage, with Rajan *et al.* (2020) reporting significantly lower frost incidence in orchards shielded by windbreaks.

Post-harvest technologies and orchard practices play an equally important role in climate

adaptation. In citrus production, specialized storage facilities are designed to preserve fruits exposed to extreme temperatures (Karagatiya *et al.*, 2023). Fruit bagging is another widely used technique. In mango production, bagging marble-sized fruits led to higher fruit retention and improved texture by preventing spongy tissue formation (Karagatiya *et al.*, 2023). Similarly, Rajan *et al.*, (2020) found that bagging pomegranates with bags reduced physiological disorders such as cracking and sunburn. Protective nets are also employed in orchards and vineyards to shield fruit against extreme radiation and hail damage (Meza *et al.*, 2023). Moreover, Geographic Information Systems (GIS) are increasingly valuable in adapting fruit production to climate change. Rajan *et al.* (2020) and Karagatiya *et al.* (2023) emphasized that GIS can identify new cultivation zones based on shifting climatic conditions. Through climate suitability mapping, specific areas can be matched with appropriate fruit species and varieties, ensuring long-term adaptation.

Crop diversity

Crop diversity emerged as an important climate change adaptation strategy in fruit tree production. Diversification enhances orchard resilience by reducing the risk of total crop failure under climate-related stresses (Abasi *et al.*, 2025). In perennial systems, diversification involves planting different cultivars or species. Chaurasia *et al.* (2023) noted that, in response to changing climatic conditions, farmers adopt market diversification by cultivating alternative fruit species that are less vulnerable to climate variability. This improves economic stability by creating multiple income streams. For example, Karamidehkordi *et al.* (2023) reported that citrus farmers who also maintained small rice plots were better able to withstand flood events than those solely reliant on citrus. Similarly, Rahimzadeh (2017) observed that crop diversification served as an adaptation strategy for apple farmers in the lowlands of the Indiana Himalayas, where rising temperatures rendered apple production less viable. Diversification into less commercially prominent but climate-resilient fruit species such as Dragon fruit, Kair, Phalsa, Pummelo, Beal, Wood apple, Aonla, Karonda, barbarous cherry, and pomegranate has also been recommended (Karagatiya *et al.*, 2023). These species generally require less moisture, exhibit lower transpiration rates and are less sensitive to temperature fluctuations, with their flowering and fruiting processes remaining relatively stable.

Cropping systems

Literature indicates that different cropping systems can be utilized to mitigate the impacts of

climate change in fruit tree production. Abasi *et al.* (2025) highlighted the use of cover crops as an adaptation strategy that reduces soil erosion caused by floods. Intercropping was also identified as an important strategy. Karagatiya *et al.* (2023) emphasized that intercropping in orchards enhances biodiversity, thereby strengthening ecosystem resilience under changing climatic conditions. Intercropping also promotes more efficient utilization of resources such as water, light and soil nutrients, while supporting beneficial insects and microorganisms that contribute to natural pest control and pollination (Rajan *et al.*, 2020).

Improved pest and disease management

Improved pest and disease management emerged as an important climate change adaptation measure. According to Karagatiya *et al.* (2023), key strategies include the development of insect and disease forecasting systems, strengthening surveillance mechanisms, establishing comprehensive pest and disease databases and implementation of efficient pest management practices. Integrated Pest Management (IPM) was also highlighted as a sustainable approach for managing pests in fruit tree production. Abasi *et al.* (2025) emphasized its role in reducing vulnerability to climate-induced pest outbreaks and Chaurasia *et al.* (2023) stressed that IPM provides a balanced and environmentally sound method for long-term pest and disease control.

Product Diversification

Product diversification emerged as an important strategy for adapting fruit tree production to climate change. According to Karagatiya *et al.*, (2023), diversifying into value-added and processed products allows farmers to utilize almost all harvested fruits, including those of lower quality, thereby reducing post-harvest losses and increasing income streams.

Farmer support mechanisms

Literature shows that fruit tree farmers benefit from various support systems that help them cope with climate change. Workshops on climate-smart farming techniques, access to meteorological data, weather forecasting and financial support to implement climate adaptation measures, are among the critical components of farmer support systems (Chaurasia *et al.*, 2023). In this regard, support services encompass extension services, government policies, insurance schemes, research, finance and meteorological information. Asare-Nuamah *et al.* (2022) emphasized the need for

financial and policy support for climate affected mango farmers in the eastern region of Ghana and Fiore *et al.* (2018) argued that incentivizing climate smart agriculture can play a major role in mitigating climate risks. Similarly, Haque *et al.* (2024) and Chaurasia *et al.* (2023) highlighted the importance of training farmers to enable them to adopt appropriate adaptation measures. Borghini, *et al.* (2023) highlighted the importance of sharing stone fruit phenological data and agro climatic requirements for different varieties of *Prunus* species. Haque *et al.* (2024) also identified natural disaster support mechanisms as an important measure to reduce financial losses and building resilience. Overall, studies indicate that farmers can strengthen their resilience, reduce vulnerability and better adapt to climate change when they have access to enabling factors and services, including credit facilities, extension services, infrastructure improvements, social capital and sustained government support (Karamidehkordi *et al.*, 2023).

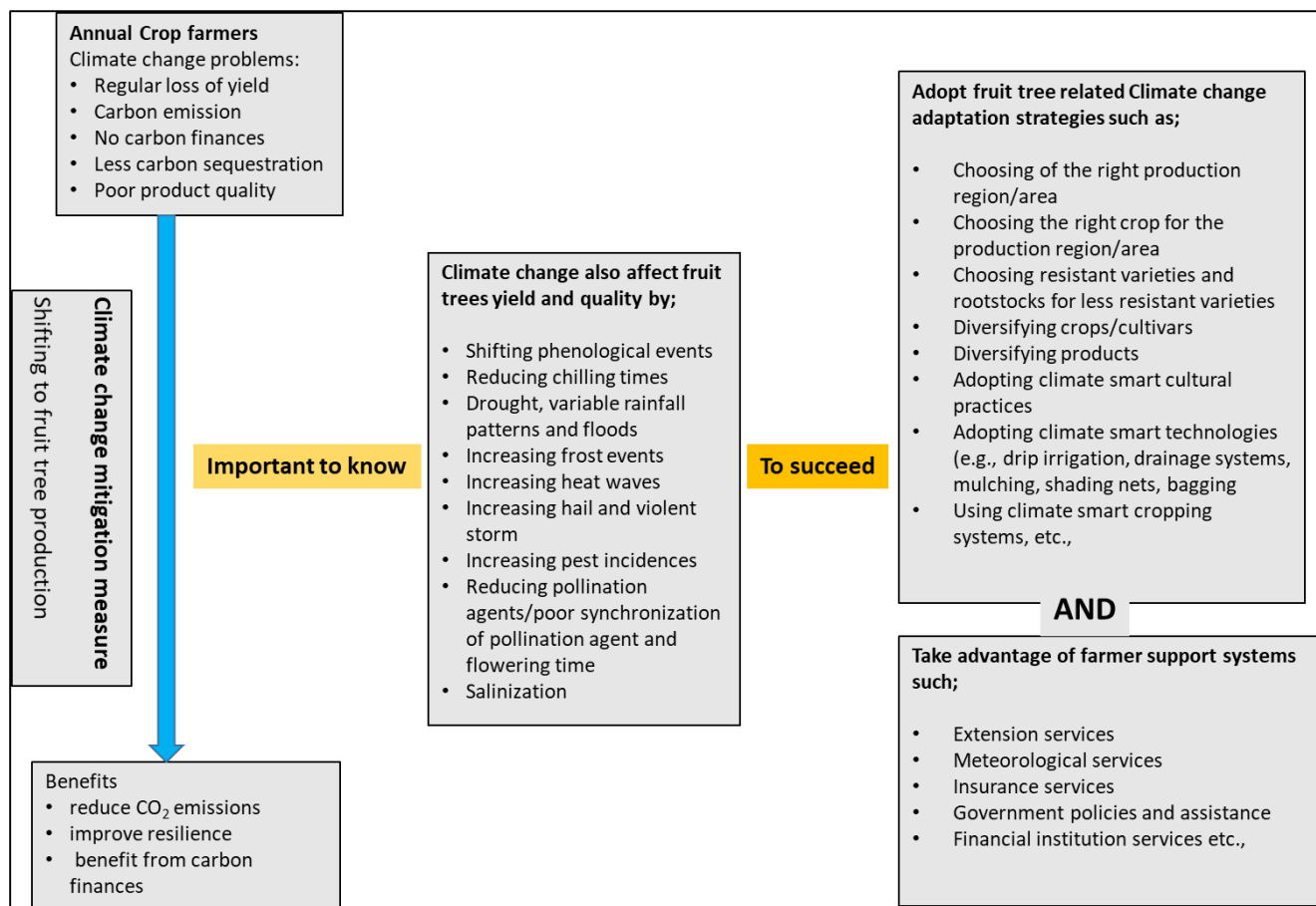


Figure 2: A model for shifting from annual crop production to fruit tree production

A model for shifting from annual crop production to fruit tree production

From the review, a conceptual model was developed to illustrate the shift from annual crop production to fruit tree farming as a climate change adaptation strategy (Figure 2). The model demonstrates that transitioning from annual crops to fruit tree enhances carbon sequestration and improves farmers' resilience to extreme climate events such as frost, windstorms, floods and cyclones. Additionally, this shift offers opportunities for farmers to participate in carbon trading. Besides, the model also recognizes that fruit tree production is not immune to the impact of climate change. Nath *et al.* (2018) emphasized that climate change affects all agricultural sectors. Understanding these risks is critical in managing this transition process. Whilst the model highlights potential adaptation strategies, farmers ultimately need to select context specific options. For instance, where relocation is not possible due to land tenure policies or migration restrictions, farmers may adopt resilience strategies such as replacing older varieties with improved climate resilient cultivars or grafting traditional varieties onto resistant rootstocks.

The model further underscores that successful adaptation extends beyond on farm strategies. It also depends on availability of support systems, including agricultural extension, meteorological services, favorable government policies, financial support, crop insurance and on-going research and innovation. These systems collectively strengthen farmers' capacity to sustain fruit tree production and secure livelihoods under changing climatic conditions.

Discussion

The study highlighted key climate change factors that influence fruit tree production, their impact on fruit yield and quality, adaptation strategies employed by farmers and the support systems that enable adaptation. Global evidence shows that temperatures have risen by 0.74 °C over the past century, accompanied by significant increases in atmospheric carbon dioxide levels (Rajan *et al.*, 2020). Projections suggest a further rise of 1.8 - 4 °C by 2100, intensifying weather variability. The findings of this study align with existing literature showing that fruit tree cultivation is highly sensitive to rising temperatures, variable rainfall, increased atmospheric carbon dioxide concentrations, and extreme weather events (Winkler *et al.*, 2013). Collectively, these factors underscore the complex challenges farmers face when shifting from annual crop production to fruit farming as a climate change adaptation strategy.

Climate change affects fruit tree production through multiple pathways. Altered phenological stages, insufficient chilling in temperate fruit trees and increased pest and disease pressure reduce fruit yields and quality (Fiore et al., 2018; Abasi et al., 2025). Extreme weather events cause physical damage to trees and fruit, while salinisation and flooding further stress production systems. Quality attributes such as sugar content and acidity in citrus, fruit colour in grapes and apples and peel integrity in citrus and pomegranate are particularly vulnerable. Both tropical and temperate fruit trees are affected, although the nature of impacts differs by species and region. Reduced yields and quality not only diminish farmers' incomes but also disrupt markets, affecting availability and consumer prices. Farmers adopting fruit production as an adaptation strategy must simultaneously develop measures to buffer fruit farming against climate risks.

This review identified several adaptation strategies available to fruit tree farmers including use of climate-resilient varieties and rootstocks, relocation of production zones and adoption of climate-smart cultural practices and technologies. Broader approaches such as crop and product diversification and climate-smart cropping systems also emerged as critical (Houston *et al.*, 2018). Importantly, successful adaptation requires enabling conditions including availability of credits, insurance services, access to extension and meteorological information, improved infrastructure and supportive government policies (Karamidehkordi et al., 2023).

Policy and practical implications are clear. Policymakers should enact policies that promote investment in breeding and dissemination of climate-resilient varieties as well as funding of research that focuses on adaptation practices. Financial incentives, technical assistance and disaster risk management systems are needed to strengthen farmer resilience. Additionally, fostering collaboration among stakeholders, including agricultural extension services, researchers, industry actors, breeders, policymakers and meteorological agencies, must provide timely climate information, promote adaptive practices and integrate traditional knowledge with modern science. For farmers transitioning from annual to perennial systems, gradual adoption strategies, such as intercropping annuals with fruit trees, selecting resistant rootstocks and adopting climate-smart cultural practices can ease the transition.

While fruit production offers long-term opportunities as a climate adaptation strategy, it also exposes farmers to new climate risks. Effective adaptation will, therefore, depend not only on the

adoption of farm-level practices but also on robust institutional support, financing, research and policy frameworks that ensure fruit farming remains a viable and resilient livelihood option in the face of climate change.

Conclusion

The study concludes that farmers shifting from annual crop production to fruit tree production as a climate change adaptation strategy must adopt a range of fruit tree-specific adaptation measures and leverage available farmer support systems to enhance resilience and productivity. Key strategies include: choosing climate-resilient cultivars and rootstocks, selecting new suitable production sites, diversifying crops and implementing climate-smart cropping systems. For established orchards, adaptation may involve the use of climate-smart technologies, such as netting, bagging, drainage systems and anti-transpirants; and climate-smart cultural practices such as pruning, drip irrigation, mulching and integrated pest management. In addition, the success of this transition depends on robust support systems, including timely meteorological and extension services, enabling government policies, access to insurance and financial support mechanisms. Strengthening these adaptation strategies and institutional frameworks will be critical for ensuring that fruit production becomes a viable sustainable pathway for farmers responding to climate change.

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