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RECENT ADVANCES IN OFF SEASON FRUIT PRODUCTION: A REVIEW

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ABSTRACT

Off-season fruit production has been developed as an important strategy to provide year-round availability of fresh fruits and to increase farmers' income to satisfy the expanding market demand. Rapid urbanisation worldwide, changing consumer preferences and advances in horticultural technologies have greatly contributed to the growth of off-season farming practices. Recent improvements in sheltered cultivation, climate smart agriculture, precision horticulture and crop regulation techniques have enabled production of high quality fruits beyond their natural growing season. Greenhouse cultivation, polyhouse technology, pruning management, irrigation scheduling, mulching, fertigation and use of plant growth regulators are significant techniques to manipulate the flowering and fruiting behaviour in different fruit crops. The efficiency and sustainability of off-season fruit production systems have been substantially enhanced in recent years by contemporary technology such as sensor-based monitoring systems, automatic irrigation, artificial intelligence, and precision farming tools. Additionally, climate-smart practices are assisting crops in reducing the negative impacts of temperature swings, water scarcity and shifting weather patterns. However, a number of obstacles still prevent these technologies from being widely used, especially in developing nations, including high initial costs, the prevalence of pests and diseases, a lack of technical expertise, and energy requirements. With a focus on contemporary cultivation methods, protected cultivation systems, climate-smart practices, and creative management approaches, this paper emphasises recent developments in off-season fruit production. Major obstacles and upcoming prospects for sustainable off-season horticulture are also covered in the review. In contemporary horticulture production systems, the use of cutting-edge technologies and integrated crop management techniques can greatly improve fruit output, quality, profitability and sustainability.

Key words : Protected cultivation, Hydroponics, Off season, Biotechnology, Genetic improvement.

Introduction

Fruit production is essential to global agriculture because it promotes food security, better nutrition, job creation, and economic growth. Due to population expansion, urbanisation, shifting eating patterns and growing consumer health consciousness, the demand for fresh fruits has skyrocketed in recent years. But the majority of fruit crops are seasonal, meaning they only bear fruit at certain times of the year. This seasonal availability frequently causes market swings, higher pricing during off-peak times and lower growers' profits. Off-season fruit production has become a key tactic in contemporary horticulture to get around these restrictions

(Singh *et al.*, 2023). The term "off-season fruit production" describes the employment of cutting-edge production technologies and crop management techniques to cultivate and harvest fruits outside of their natural growing season (Castilla *et al.*, 2002). The primary goal of off-season production is to increase farmers' revenue and market opportunities while guaranteeing year-round supply of high-quality fruits. To control flowering and fruiting behaviour in various fruit crops, a variety of methods are frequently employed, including protected culture, crop regulation, pruning, irrigation management, fertigation, and the administration of plant growth regulators (Kumar and Sharma, 2024). In various regions

of the world, crops like mango, guava, strawberry, citrus, pomegranate, papaya, and grapes are being grown under off-season production techniques (Duckett *et al.*, 2018).

Off-season fruit production is now much more efficient thanks to recent developments in protected cultivation methods. For improved plant growth and productivity, regulated climatic conditions that help regulate temperature, humidity, light intensity, and carbon dioxide concentration are provided by greenhouses, polyhouses, shade-net structures, and low tunnels (Patel *et al.*, 2025). Greenhouse and controlled-environment technologies are crucial for increasing off-season horticulture yield, according to several protected cultivation studies (Gaur and Dhaliwal, 2003; Jindal and Sharma, 2000). These technologies encourage early flowering and fruiting, while shielding crops from unfavourable weather conditions like frost, heavy rainfall, heat stress and strong winds. Additionally, protected agriculture increases the efficiency of water and nutrient use, lowers the prevalence of pests and diseases, and improves fruit quality. One of the main issues influencing fruit production globally is climate change. Flowering, pollination, fruit set and fruit quality are all adversely affected by rising temperatures, erratic rainfall patterns, drought stress, and extreme weather events (FAO, 2022). The global food supply and agricultural output may be greatly impacted by climate variability and rising temperatures, according to previous research (Rosenzweig and Parry, 1994; Schmidhuber and Tubiello, 2007).

In this regard, precision farming techniques and climate-smart horticulture are becoming more significant in off-season fruit producing systems. The Internet of Things (IoT), sensor-based irrigation systems, automated climate control, artificial intelligence and remote sensing technologies are examples of contemporary innovations that are assisting farmers in maximising resource utilisation and enhancing crop productivity in the face of changing climatic conditions (Reddy *et al.*, 2024). In light of shifting environmental conditions, resource management techniques and climate adaptation are becoming more crucial for sustainable horticulture production (Pathak *et al.*, 2012). Real-time monitoring of soil moisture, nutrient status, and environmental factors is made possible by precision horticulture techniques, which boost productivity and sustainability. Off-season fruit production is another important function of plant growth regulators (PGRs) (Langhans *et al.*, 1997). Fruit crops are frequently treated with chemicals such as paclobutrazol, gibberellic acid, naphthalene acetic acid, and ethephon to control flowering, fruit set, vegetative development and ripening (Sharma and Verma, 2023). Crop control strategies, such as

irrigation stress management in mango, pruning management in grapes and bahar treatment in guava and pomegranate, have demonstrated encouraging outcomes in changing the production season and enhancing fruit output and quality. In a same vein, mulching, fertigation, and hydroponic farming are being used more frequently to produce fruit effectively and sustainably in protected environments (Rajan *et al.*, 2021 and Kader *et al.*, 2011).

Even while off-season fruit producing technology have advanced remarkably, a number of obstacles still prevent their widespread implementation. For small and marginal farmers in particular, high initial investment costs, technological complexity, a shortage of experienced personnel, energy requirements, and pest and disease outbreaks continue to be significant obstacles (Kaur *et al.*, 2023). Furthermore, poor maintenance of protected structures may foster the growth of physiological illnesses and fungal diseases. As a result, there is an increasing demand for ecologically friendly, economical, and sustainable production methods that can increase profitability while reducing negative effects on the environment (Pimentel *et al.*, 1982). In order to improve long-term horticultural sustainability and environmental protection, agroecological production systems and sustainable agriculture approaches are being pushed more and more (Altieri, 1995 and Uphoff, 2002).

Recent research efforts are mainly focused on developing climate-resilient fruit varieties, energy-efficient greenhouse systems, automated irrigation technologies, and integrated crop management practices for sustainable off-season fruit production. The integration of biotechnology, precision agriculture and digital farming tools is expected to revolutionize the horticulture sector in the coming decades (Rana *et al.*, 2025). Sustainable intensification strategies are also gaining importance for improving productivity while minimizing environmental degradation in horticultural systems (Pretty and Bharucha, 2014). Furthermore, government support programs, training initiatives and technological advancements are encouraging growers to adopt modern off-season cultivation practices for higher productivity and income generation (Sharmila *et al.*, 2018).

Modern Off-season techniques

In guaranteeing year-round fruit availability, increased profitability, and improved market stability, contemporary off-season fruit producing techniques have revolutionised the horticultural industry. Many methods are used to control the flowering and fruiting behaviour of various fruit crops, including hydroponics, precision horticulture, mulching, fertigation, irrigation scheduling, pruning

management, plant growth regulators, and flowering regulation. Under shifting climate conditions, these technologies enhance fruit quality, productivity, and sustainability (Monselise and Goldschmidt, 1982).

Flowering regulation

One of the most crucial methods in off-season fruit production is flowering management. Fruit development, yield and harvesting season are all influenced by flowering. Mango, guava, citrus, grapes, and pomegranate are just a few of the tropical and subtropical fruit crops whose flowering can be controlled using crop management techniques and environmental control to produce fruits during non-traditional seasons (Davenport, 2007). Guava and pomegranate farming frequently uses crop regulation techniques like bahar treatment. In order to promote flowering during a certain season, bahar treatment entails trimming, fertiliser control, root exposure and withholding irrigation. This method aids growers in producing crops when prices are higher and market demand is strong. According to studies, choosing the right bahar has a big impact on fruit productivity and quality (Singh, 2001).

Fruit crops' flowering behaviour is also influenced by environmental conditions as temperature, humidity, photoperiod, and water stress. In citrus and mango cultivation, controlled drought stress followed by irrigation is frequently used to induce flowers (Singh *et al.*, 2026). By inhibiting vegetative growth and encouraging floral bud differentiation, paclobutrazol treatment has demonstrated encouraging results in initiating blooming in mangoes during off-season conditions (Salazar-García and Vasquez-Valdivia, 1997). The relevance of molecular and biotechnological techniques like CRISPR/Cas9, gene editing and flowering-related gene expression studies in controlling off-season flowering in perennial fruit crops has been further underlined by recent study. By enabling precise blooming control and increased climatic resilience, these cutting-edge technologies are predicted to completely transform fruit production systems in the future.

Pruning management

Another crucial method for efficient off-season fruit production is pruning management. Pruning improves light penetration, increases air circulation within the canopy, controls vegetative development and promotes the emergence of new shoots (Westwood, 1993). In many fruit crops, proper pruning techniques improve blooming, fruit set, and fruit quality. The harvesting season and crop maturity in grape farming are significantly influenced by the timing of pruning. In tropical and subtropical regions,



Fig. 1 : Flowering Regulation in Mango using Paclobutrazol [adapted from Davenport (2007), Whiley (1993) and (Poerwanto *et al.*, 2006)].

summer pruning and cane pruning are commonly used to produce grapes during the off-season. In a similar vein, guava trimming enhances fruit quality and size while controlling flowering flushes. Scientific pruning greatly enhances guava flowering and yield performance, according to early research by Pal and Lal (1980).

By preserving appropriate canopy design and lowering excessive humidity within the plant canopy, pruning also helps lower the occurrence of pests and diseases. For improved canopy management and productivity, modern orchard systems are increasingly using training and pruning techniques such as espalier, trellis systems, open vase systems, and central leader systems. Robotic and AI-assisted pruning systems in orchards and vineyards have been made possible by recent technical developments. Artificial intelligence and machine vision-equipped autonomous pruning robots can carry out accurate pruning tasks with less effort. Due to growing labour costs in horticultural production systems, these technologies are becoming more and more significant as they increase operational efficiency.

Plant Growth regulators

In contemporary off-season fruit production, plant growth regulators (PGRs) are widely employed to control vegetative growth, ripening, flowering, and fruit setting. These substances affect the plant's physiological and biochemical processes and assist farmers in controlling crop phenology to meet consumer demand. One of the most popular plant growth regulators for encouraging mango blossom is paclobutrazol. Gibberellin biosynthesis is inhibited, vegetative development is suppressed, and floral bud formation is encouraged. According to studies, under the right environmental circumstances, paclobutrazol-treated mango trees can be made to flower nearly all year round (Whiley, 1993).

In many fruit crops, additional growth regulators such as gibberellic acid (GA₃), ethephon, naphthalene acetic acid (NAA) and cycocel are also employed to increase fruit size, promote blooming, decrease fruit drop and synchronise fruit maturity. Paclobutrazol and dormancy-breaking agents have been used to successfully trigger off-season blooming and fruiting in citrus and mangosteen (Poerwanto *et al.*, 2006). Because environmental conditions may be more successfully managed in shielded growing systems, plant growth regulators are very helpful. However, overuse or inappropriate application of PGRs may have detrimental effects on environmental safety and plant physiology. Therefore, for sustained horticulture output, appropriate dosage and scientific management techniques are required (Rademacher *et al.*, 2015).

Irrigation scheduling

Effective irrigation timing affects blooming, nutrient uptake, fruit setting, and general plant growth, all of which are critical to off-season fruit yield. In order to promote blooming and control crop cycles, controlled water stress management is frequently used in the production of mangoes, citrus, and pomegranates. In contemporary horticulture, drip irrigation systems are becoming more and more popular since they precisely apply water to the root zone. These systems minimise nutrient losses, increase water efficiency and preserve ideal soil moisture levels. The efficiency and sustainability of irrigation are further improved by smart irrigation systems that incorporate climate-monitoring devices and soil moisture sensors (Jat *et al.*, 2016).

Artificial intelligence, remote sensing, drones, and Internet of Things-based systems are used in recent developments in precision irrigation technology to monitor soil moisture and environmental variables in real time. In protected cultivation systems, automated irrigation systems optimise water application, lower labour costs, and increase fruit output. Fruit quality attributes including size, colour, sweetness, and shelf life are all enhanced by appropriate irrigation schedule. The impact of climate change and water shortage on global horticulture output has made efficient water management more crucial (Duckett *et al.*, 2018).

Mulching practices

In contemporary off-season fruit production systems, mulching is a crucial technique for maintaining soil moisture, controlling soil temperature, inhibiting weed growth, and enhancing soil fertility. While artificial mulches like plastic films aid in lowering evaporation and weed development, organic mulches like straw, dry leaves, compost, and agricultural residues enhance soil microbial

activity and nutrient availability. In strawberry, watermelon, papaya and vegetable-based fruit production systems, plastic mulching is frequently employed to encourage early crop establishment and enhance fruit quality. Additionally, reflective mulches enhance light dispersion throughout the canopy and lessen insect infestation. Mulching increases fruit yield, root growth, and water use efficiency under protected cultivation settings, according to studies. Mulching also contributes significantly to climate-smart agriculture by preventing soil erosion and preserving beneficial soil microclimatic conditions. In off-season fruit production systems, mulching greatly increases productivity and sustainability when combined with drip irrigation and fertigation systems.

Fertigation and hydroponics

In contemporary off-season fruit production methods, fertigation and hydroponic technologies are becoming more and more crucial. Fertigation is the process of applying fertilisers using irrigation systems, particularly drip irrigation, which enables accurate nutrient delivery straight to the root zone. This method increases fruit yield and quality, decreases fertiliser waste, and improves nutrient uptake efficiency. Plants are grown in nutrient-rich water solutions under carefully regulated environmental conditions using hydroponics, a soilless growth method. Effective water use, less soil-borne illnesses, quicker plant growth and year-round output are just a few benefits of hydroponic farming. Hydroponic systems are being used more and more to grow crops including strawberries, blueberries, raspberries, and exotic fruits. Due to their high production and effective land utilisation, vertical farming and hydroponic greenhouse systems are becoming more and more popular in urban horticulture. Hydroponic fruit production methods are becoming more profitable and efficient because to automated nutrient delivery systems, computerised climate management and AI-assisted monitoring technologies (Verma *et al.*, 2024).

Precision Horticulture technologies

In combining robotics, drones, remote sensing, artificial intelligence and sensor-based monitoring systems, precision horticulture technologies are transforming off-season fruit producing systems. Real-time monitoring of environmental parameters like temperature, humidity, soil moisture, nutrient levels and pest occurrence is made possible by these technologies. The usage of drones with thermal and multispectral sensors for crop health evaluation, precision spraying, disease diagnosis, and orchard monitoring is growing. Irrigation and nutrient management are optimised using sensor-based systems

based on crop needs. Growers can anticipate disease outbreaks, nutrient deficits and flowering behaviour with the use of artificial intelligence and machine learning techniques. Other cutting-edge tools in contemporary horticulture include robotic harvesting and autonomous orchard management systems. These technologies increase production, decrease the need for labour, and improve operational accuracy. By reducing resource waste and increasing environmental efficiency, precision horticulture promotes sustainable fruit production (Westwood *et al.*, 1993).

Climate-Smart Fruit production

A crucial strategy for guaranteeing sustainable horticulture production in the face of shifting climatic conditions is climate-smart fruit production. Fruit crop yield and quality are being greatly impacted globally by rising global temperatures, erratic rainfall patterns, drought stress and extreme weather events (FAO, 2017). Using cutting-edge technologies and sustainable management techniques, climate-smart horticulture aims to lower greenhouse gas emissions, increase productivity and strengthen climate resilience. By incorporating climate-smart techniques into off-season fruit producing systems, year-round fruit availability is maintained while environmental effects are reduced (Winkler, 1974).

Climate Change effects on Fruit production

One of the biggest risks to horticulture production systems worldwide is climate change. Fruit crops' flowering, pollination, fruit setting, and fruit quality are all directly impacted by changes in temperature, rainfall, humidity, and sun radiation (Lobell and Gourdj, 2012). In crops including mango, citrus, grapes and apples, high temperature stress frequently results in flower drop, poor fruit set, sunburn damage and decreased fruit quality. Drought and erratic rainfall further limit plants' access to water and ability to absorb nutrients. Fruit plantations in temperate and subtropical countries are increasingly suffering from heat waves and frost damage. Wheeler and von Braun (2013) state that if sustainable adaptation strategies are not implemented, climate change is predicted to drastically lower agricultural productivity in many developing nations. The prevalence of pests and diseases in fruit crops is also impacted by changing climate conditions. Insect pests, viral illnesses, and fungal diseases all benefit from warmer temperatures and higher humidity. For sustainable fruit production, climate-resilient horticulture systems are therefore becoming more and more crucial.

Water management and Smart irrigation

One of the most important aspects of climate-smart

fruit cultivation is effective water management. Because of decreasing groundwater levels and erratic rainfall patterns, water shortage is becoming a serious problem. Drip irrigation, micro-sprinklers, and sensor-based irrigation systems are examples of contemporary irrigation technologies that increase water use efficiency and decrease waste (Feres and Soriano, 2007). By delivering water straight to the plant's root zone, drip irrigation reduces evaporation and runoff losses. Fruit crops including pomegranates, citrus, mangoes, and grapes benefit greatly from this technique. Real-time irrigation scheduling based on crop water requirements is made possible by smart irrigation technologies combined with weather-based monitoring systems and soil moisture sensors (Jones, 2004).

Water recycling and rainwater collection are two more crucial climate-smart horticultural practices. Rainwater that has been collected can be kept and used for irrigation during dry spells. Mulching techniques also enhance the soil's ability to retain water and preserve soil moisture. In addition to boosting fruit yield, effective water management promotes long-term environmental sustainability.

Temperature and Environmental control

A further important aspect of climate-smart off-season fruit growing is temperature control. Many horticultural crops are negatively impacted by high temperature stress in terms of flowering, pollination, and fruit development. Greenhouses, polyhouses, and shade-net houses are examples of protected cultivation buildings that help control environmental conditions and shield crops from severe weather occurrences (Stanghellini, 2014).

To maintain ideal temperatures and humidity levels, contemporary greenhouse systems are outfitted with cooling pads, fogging systems, ventilation systems, thermal screens, and automated climate control technologies. These systems lessen environmental stress on plants while increasing crop growth and output (Zhao *et al.*, 2017). In tropical and subtropical areas, shade-net constructions are frequently employed to shield fruit crops from heat stress and excessive sun radiation. For early crop establishment and improved fruit quality, low tunnels and plastic mulches also aid in controlling the temperature of the soil and canopy. Under off-season growing techniques, controlled climatic conditions encourage consistent flowering, better fruit set, and improved fruit colouration. For fruit production to be sustainable in the face of changing climatic circumstances, climate-controlled horticulture is becoming more and more crucial.

Sustainable and Eco-Friendly practices

A few of the main goals of climate-smart fruit producing systems is sustainability. Environmentally friendly methods that preserve natural resources while maintaining high production are the focus of modern gardening. For sustainable fruit production, organic farming, integrated nutrient management, integrated pest management, and conservation agriculture are all strongly encouraged (Pretty, 2008). Compost, biofertilizers, and organic manures increase microbial activity and soil fertility while lowering reliance on artificial fertilisers. By using pheromone traps, resistant cultivars, biological control agents, and cultural techniques, integrated pest management (IPM) techniques reduce the need for pesticides. These methods enhance food safety and lessen pollution in the environment.

In climate-smart horticulture, agroforestry systems and mixed cropping techniques are also becoming more and more popular. These systems increase carbon sequestration, decrease soil erosion, and boost biodiversity. Sustainable fruit production is further aided by renewable energy technology like solar-powered irrigation systems and energy-efficient greenhouses. Through effective resource usage and lower greenhouse gas emissions, climate-smart horticulture also encourages the reduction of carbon footprints. Long-term food security and environmental preservation depend on the adoption of sustainable agricultural methods.

Precision and Digital Horticulture

Climate-smart fruit production systems heavily rely on recent developments in precision horticulture and digital agriculture. Horticultural resource management and production efficiency are being enhanced by technologies like artificial intelligence (AI), remote sensing, drones, the Internet of Things (IoT) and geographic information systems (GIS) (Gebbers and Adamchuk, 2010). Crop health, temperature, humidity, soil moisture and nutrient levels are all continuously monitored by sensors placed

in orchards and greenhouses. These technologies assist growers in making decisions in real time on climate control, pest management, fertigation and irrigation. Precision spraying, crop monitoring, and orchard mapping are all using drone technology more and more.

Fruit crop disease outbreaks, flowering patterns, and nutritional deficits can all be predicted using machine learning and AI-based systems. Additionally, manpower needs and operating expenses are decreased by digital agricultural technologies. Under climate change, precision horticulture promotes sustainable off-season fruit production systems, increases productivity and reduces environmental consequences (Van Henten *et al.*, 2002).

Protected Fruit cultivation

One of the most cutting-edge methods for producing fruit during the off-season is protected fruit gardening. It entails using structures like greenhouses, polyhouses, and shade-net houses to grow crops in regulated or partially controlled environmental conditions. These systems enhance productivity, fruit quality and year-round availability while shielding crops from adverse weather conditions (Wittwer *et al.*, 1995).

Greenhouse cultivation

One of the most successful protected cultivation techniques in contemporary horticulture is greenhouse cultivation. A greenhouse is a framed building coated with transparent materials, like glass or polyethylene, that permits sunlight to enter while preserving regulated environmental conditions (Jensen, 2002). For the best possible plant growth, greenhouses assist in controlling temperature, humidity, light intensity, and carbon dioxide concentration. A growing number of fruit crops, including blueberries, strawberries, grapevines, and exotic fruits, are grown in greenhouse systems for off-season production (Zhao *et al.*, 2019). Flowering, fruit set, fruit quality, and harvesting time are all enhanced by controlled environmental conditions. Additionally, greenhouses shield

Table 1 : Major climate-smart technologies and their benefits in fruit production.

Technology	Major function	Benefits
Drip Irrigation	Efficient water delivery	Water conservation and improved yield
Greenhouse Cultivation	Environmental control	Protection from extreme climate
Mulching	Soil moisture conservation	Reduced evaporation and weed growth
Sensor-Based Irrigation	Real-time monitoring	Precision water management
Drones & Remote Sensing	Crop monitoring	Early disease and stress detection
Solar-Powered Irrigation	Renewable energy use	Reduced energy cost and sustainability
AI-Based Monitoring	Decision support system	Better crop management efficiency

Modified from climate-smart horticulture and precision agriculture studies (Feres and Soriano, 2007; Jones, 2004; Gebbers and Adamchuk, 2010).

crops from heat stress, high winds, heavy rainfall and cold (Singh *et al.*, 2024).

Cooling pads, fogging systems, ventilation fans and computerised climate control systems are just a few of the technology found in contemporary greenhouses. (Sthapit *et al.*, 2012) These technologies lessen crop stress from the environment and increase production efficiency. Due to its effective use of nutrients and water, hydroponic greenhouse systems are also growing in popularity (Sethi and Sharma, 2008).

Polyhouse technology

Another popular protected culture method in fruit production systems is polyhouse cultivation. Polyethylene sheets covering polyhouses provide an ideal environment for crop growth. Polyhouses offer greater crop protection and environmental control than open-field farming (Singh and Sirohi, 2006). Strawberries, papayas, cucumbers, and other high-value horticultural crops are frequently grown in polyhouse systems. Higher yield, better fruit quality, and early flowering are all encouraged by these structures. Additionally, crops are shielded by polyhouses from pest damage, frost, hailstorms and extreme rainfall. To enhance water and nutrient management, polyhouses frequently use drip irrigation and fertigation systems. Due to its lower operating costs, naturally ventilated polyhouses are appropriate for tropical and subtropical areas. For commercial off-season fruit production, climate-controlled polyhouses with automated heating and cooling systems work incredibly well (Zilberman *et al.*, 2012).

Shade-Net cultivation

A low-cost protected growing technique called shade-net cultivation helps horticultural crops avoid heat stress and excessive solar radiation. By lowering the temperature and light intensity surrounding the crop canopy, shade nets produce a beneficial microclimate (Castellano *et al.*, 2008). Fruit crops including dragon fruit, kiwis, strawberries, and pomegranates are frequently raised in nurseries, propagated, and cultivated in shade-net houses. These structures increase water use efficiency, stop leaf burning, and lessen moisture loss. Depending on the needs of the crop, different coloured shade nets such as green,

black, red, and white are utilised. Insect infestation and bodily harm from heavy rains and winds are also lessened by shade-net systems. Shade-net buildings are a great option for small and medium-sized horticultural producers because of its inexpensive installation costs and ease of maintenance (Sambo *et al.*, 2019).

Fertigation and Hydroponic systems

Hydroponic systems and fertigation are crucial elements of protected fruit production. Applying water-soluble fertilisers via irrigation systems, particularly drip irrigation, is known as fertigation. This technique greatly increases fertiliser utilisation efficiency and enables precision nutrient administration straight to the root zone (Hagin and Lowengart, 1996). Plants are cultivated in nutrient-rich liquids under carefully monitored conditions in hydroponic cultivation, a soilless production method (Incrocci *et al.*, 2020). Effective water use, fewer soil-borne illnesses, quicker plant growth and year-round fruit production are just a few benefits of this technology. Hydroponic systems are being used more and more to grow crops like strawberries and exotic berries (Resh, 2013).

Challenges and solutions in off-season fruit production

There are many benefits to off-season fruit cultivation, including year-round fruit supply, increased market pricing, increased farmer income and enhanced resource utilisation. However, the effective implementation of off-season cultivation methods is constrained by a number of technical, financial, environmental and management-related issues. Production efficiency and profitability are frequently decreased by factors such high production costs, the prevalence of pests and diseases, climate fluctuation, workforce shortages and a lack of technical expertise. In order to overcome these constraints and guarantee long-term sustainability in off-season horticulture, contemporary technical solutions and sustainable management techniques are crucial.

Pest and Disease management

One of the biggest problems with off-season fruit production systems is pest and disease infestation,

Table 2 : Comparison of Major protected Cultivation Systems.

System	Main Features	Major Advantages	Suitable Crops
Greenhouse	Fully controlled environment	High productivity and quality	Strawberry, grape, blueberry
Polyhouse	Polyethylene-covered structure	Cost-effective protection	Papaya, cucumber, strawberry
Shade-Net House	Reduced solar radiation	Protection from heat stress	Dragon fruit, nursery plants
Hydroponic System	Soilless cultivation	Efficient nutrient and water use	Strawberry, exotic fruits

Modified from greenhouse management and protected horticulture studies.

especially in protected cultivation settings. Fungal, bacterial, and viral infections frequently thrive in situations with high humidity, dense canopy growth, and regulated circumstances (Agrios, 2005). Fruit crops cultivated in greenhouses and polyhouses are particularly vulnerable to anthracnose, wilt, root rot, powdery mildew and downy mildew. In off-season fruit production, insect pests such as aphids, whiteflies, thrips, mites, and fruit borers also result in significant financial losses. Continuous cropping under protected structures can occasionally lead to a decrease in natural biological control mechanisms and an increase in pest populations. Overuse of chemical pesticides can result in food safety issues, environmental contamination and pesticide resistance.

One of the best options for long-term pest management in horticulture is integrated pest management, or IPM. IPM reduces pest prevalence by combining pheromone traps, cultural techniques, biological control, resistant cultivars, and need-based pesticide use (Dent, 2000). In greenhouse production systems, the employment of biological control agents including *Bacillus subtilis*, *Trichoderma*, and predatory insects is growing. Growers are also able to detect infections early and minimise crop losses thanks to modern sensor-based monitoring and AI-assisted disease detection technology (Van Lenteren *et al.*, 2000).

High production cost

Adoption of off-season fruit production technology is still hampered by high initial and operating expenses. Greenhouses, polyhouses, hydroponic systems and temperature control equipment are examples of protected cultivation structures that demand a significant initial investment (Jensen and Malter, 1995). Establishing these systems might be financially challenging for small and marginal farmers. The total cost of production is further raised by operational expenses such as energy, irrigation, fertilisers, labour, maintenance and pest control. Technical know-how and routine maintenance are necessary for advanced technologies including hydroponic nutrition management systems, climate control units, and automated irrigation systems (Kader, 2002). Farmers can more successfully implement contemporary horticulture technologies with the support of government subsidies, financial assistance programs and low-interest agricultural loans. Operating costs can be decreased by using solar-powered irrigation systems, inexpensive polyhouses and naturally ventilated buildings. Farmer cooperatives and community-based agricultural methods may also reduce infrastructure costs and provide access to contemporary technologies.

Technologies for protected farming that are affordable and appropriate for small-scale farmers are constantly being developed by research organisations. Using sustainable energy systems and locally sourced materials can further lower production costs without sacrificing profitability or productivity.

Labour and technical constraints

As off-season fruit production systems to be successfully managed, skilled manpower and appropriate technological knowledge are necessary. Pruning, fertigation, climatic control, pollination, hydroponic management, and disease monitoring are examples of operations that call for skilled personnel and scientific knowledge (Hartmann *et al.*, 2011). Farmers, who lack technical knowledge frequently manage their crops poorly and produce less. Horticulture is experiencing a growing number of labour shortages as a result of rural workers migrating to non-agricultural industries and urbanisation. Systems for protected cultivation are labour-intensive and need constant upkeep and observation. Skilled labour is especially needed for trimming, training, harvesting and pollination control.

To increase farmers' technical proficiency and understanding of protected horticulture systems, training programs, farmer awareness campaigns, and agricultural extension services are crucial. Farmers are receiving more and more assistance with crop management and decision-making processes from digital agricultural tools, mobile applications, and online advisory services. In contemporary horticulture, automation and robotics are also showing promise as solutions to the workforce problem. AI-based monitoring systems, automated irrigation systems and robotic harvesting systems all contribute to lower labour costs while increasing accuracy and operational effectiveness. Therefore, it is anticipated that the future of off-season fruit production systems will be significantly influenced by the use of smart technology.

Environmental and Sustainability issues

In off-season fruit production systems, environmental sustainability is a major problem. Soil health, water quality, and ecosystem stability may be adversely affected by excessive use of fertilisers, pesticides, plastics, and energy resources (Tilman *et al.*, 2002). Environmental contamination and disposal issues arise from plastic trash produced by mulching films, drip irrigation systems, and greenhouse covers. Overuse of chemical pesticides and fertilisers can contaminate groundwater, degrade soil, and lower beneficial microbial activity. Greenhouse gas emissions and higher manufacturing costs are further consequences of energy-intensive greenhouse systems.

Table 3 : Major challenges and their possible solutions in off-season fruit production.

Challenges	Major Problems	Possible Solutions
Pest & Disease Incidence	High humidity and protected conditions	Integrated Pest Management (IPM)
High Production Cost	Expensive infrastructure and maintenance	Subsidies and low-cost technologies
Labour Shortage	Skilled labour requirement	Automation and robotics
Water Scarcity	Limited irrigation resources	Drip irrigation and rainwater harvesting
Environmental Pollution	Excessive chemical and plastic use	Organic farming and biodegradable materials
Climate Variability	Temperature and rainfall fluctuations	Climate-smart horticulture practices

Modified from studies on protected horticulture, climate-smart agriculture and sustainable fruit production systems.

Horticultural production systems are more susceptible to drought, harsh temperatures and water scarcity as a result of climate change.

Organic farming, integrated fertiliser management, the use of renewable energy, rainwater collection and biological pest control are examples of sustainable horticulture techniques that are crucial for reducing environmental effects. For ecologically friendly horticultural systems, reusable greenhouse materials and biodegradable mulches are being encouraged more and more. Sensor-based irrigation, fertigation and AI-assisted resource management are examples of precision agriculture technologies that increase input usage efficiency and lower environmental pollution. Sustainable fruit production is further supported by energy-efficient greenhouses and solar-powered irrigation systems. The integration of contemporary technologies with ecologically conscious management techniques is essential to the long-term viability of off-season horticulture (Lal *et al.*, 2004).

Future Scope of Off-season farming

Rapid developments in biotechnology, climate-smart horticulture, protected cultivation and smart farming technologies all point to a bright future for off-season fruit production. The use of sophisticated fruit production methods is being encouraged by factors such as growing populations, urbanisation, shifting dietary choices, and year-round market demand for fresh fruits (Gill *et al.*, 2009). Conventional agriculture is rapidly giving way to sustainable, technologically advanced and precision-based production methods in modern horticulture. Future developments in off-season farming methods are anticipated to enhance fruit quality, production, profitability, and environmental sustainability.

Artificial Intelligence and Smart Farming

Smart farming technology and artificial intelligence (AI) are becoming crucial parts of contemporary horticultural systems. In order to improve production efficiency and decision-making processes, AI-based solutions assist in analysing crop growth, environmental

circumstances, nutrient status and disease symptoms (Liakos *et al.*, 2018). Growers can monitor crops in real time and adjust management techniques based on plant needs thanks to these technology. Soil moisture, humidity, temperature, and nutrient availability are all continuously monitored by Internet of Things (IoT)-based sensors placed in orchards and protected production buildings. By automatically adjusting water and fertiliser application based on crop need, smart irrigation and fertigation systems increase resource efficiency and lower production costs (Pandey and Mishra, 2021).

In fruit production systems, drone technology and remote sensing are also being utilised more frequently for crop monitoring, orchard mapping, disease detection, and precision spraying. Under various environmental conditions, machine learning algorithms aid in the prediction of agricultural output, flowering behaviour and disease outbreaks. In off-season horticulture systems, these technologies greatly lower labour requirements and increase sustainability. Automated greenhouse management systems are being further supported by recent advancements in digital agriculture. For improved crop production, climate-control technology combined with AI systems can automatically adjust temperature, humidity, ventilation, and cooling. Thus, in the upcoming decades, off-season fruit producing systems are anticipated to undergo a transformation thanks to smart farming technologies.

Climate-Resilient fruit production systems

One of the main issues influencing horticultural output globally is climate change. Flowering, fruit setting, production, and fruit quality are all adversely affected by rising temperatures, erratic rainfall patterns, drought stress and extreme weather events. Thus, climatic resilience and sustainable resource management must be the main priorities of future horticulture systems (Howden *et al.*, 2007). In order to reduce climatic hazards in fruit production systems, protected cultivation structures including greenhouses, polyhouses, and climate-controlled systems are anticipated to grow quickly. These structures

shield plants from bad weather while assisting in maintaining ideal climatic conditions for crop growth. Crop productivity and resource efficiency are increased by automated cooling, ventilation, and humidity management systems combined with advanced greenhouse technology (Shamshiri *et al.*, 2018).

In situations where water is scarce, water-efficient technologies like drip irrigation, rainwater collection, and sensor-based irrigation systems will become more crucial. The sustainability of fruit production systems will be further enhanced by climate-smart horticultural techniques as mulching, conservation agriculture, integrated nutrient management, and biological pest control (Singh *et al.*, 2019). In order to lower operating costs and greenhouse gas emissions, renewable energy solutions like solar-powered irrigation systems and energy-efficient greenhouse structures are also becoming more and more important. In order to provide food security and environmental preservation, future off-season fruit production systems are anticipated to integrate climate-smart technologies with sustainable farming practices (Jensen *et al.*, 2002).

Biotechnology and Genetic improvement

Future off-season fruit producing methods are anticipated to be heavily influenced by biotechnology and genetic advancement. New possibilities for enhancing fruit crop productivity, quality and stress tolerance are being created by developments in molecular biology, genomics, tissue culture, and gene editing technologies (Tester and Langridge, 2010). Fruit crop varieties with improved blooming behaviour, disease resistance, heat tolerance, drought tolerance, and increased fruit quality are being developed through the use of gene editing technologies like CRISPR/Cas9. Researchers are using molecular breeding methods to find the genes in horticulture crops that control flowering, fruit growth and climate adaption.

Fruit crops are increasingly using tissue culture and micropropagation techniques to quickly multiply disease-free planting material. Under protected agriculture systems, these methods increase crop productivity, plant health, and uniformity. Through genetic and physiological changes, biotechnology also helps to improve fruit postharvest quality and shelf life. In order to create robust and sustainable fruit production technologies, future research is anticipated to combine biotechnology with climate-smart horticulture systems and precision farming. Programs for genetic enhancement will consequently be essential to maintaining consistent fruit output in the face of shifting climate circumstances.

Automation and Sustainable Horticulture

In horticulture, automation is becoming a significant remedy for labour shortages and growing production costs. In order to increase operational efficiency, modern fruit production systems are progressively utilising robotic technology, automated irrigation systems and AI-assisted monitoring tools (Duckett *et al.*, 2018). For crops including apples, strawberries, and grapes, robotic harvesting systems with machine vision and artificial intelligence capabilities are being developed. These technologies minimise crop damage during harvesting operations, increase harvesting precision, and lessen reliance on labour. In commercial horticulture, automated technologies for sorting, grading, pruning, and packaging are also increasing the effectiveness of postharvest management. With little assistance from humans, autonomous greenhouse management systems assist in controlling environmental factors including temperature, humidity, and fertiliser delivery. According to Van Henten *et al.* (2002), precision automation methods decrease environmental contamination while increasing the efficiency of water and fertiliser use.

It is anticipated that future horticultural systems will prioritise eco-friendly production methods and sustainability. For sustainable off-season fruit production, biodegradable mulches, renewable energy systems, recyclable greenhouse materials and low-carbon agricultural techniques will become more crucial. Due to the growing demand for urban food and the scarcity of agricultural land, urban gardening, rooftop farming, hydroponics, and vertical farming systems are also anticipated to grow quickly (Tripathi *et al.*, 2020). Harvesting and crop management activities are becoming more precise because to the integration of advanced robotic systems with computer vision technologies (Zhao *et al.*, 2016). In order to ensure increased productivity and long-term environmental sustainability, future off-season fruit production systems are anticipated to become more automated, sustainable, climate-resilient, and technology-driven (Vashisth *et al.*, 2020).

Conclusion

A significant and cutting-edge strategy for guaranteeing year-round fruit availability, raising farmers' incomes, and strengthening the sustainability of contemporary horticultural systems is off-season fruit production. Globally, fruit production methods have been drastically altered by the quick development of protected cultivation, climate-smart agriculture, precision horticulture, biotechnology, and automation (FAO, 2021). Growers are now able to successfully control blooming

and fruiting behaviour under controlled environmental conditions because to techniques like fertigation, hydroponics, greenhouse cultivation, flowering regulation, pruning management, and smart irrigation systems. In order to reduce the negative consequences of climate change, water scarcity, and environmental degradation on fruit production systems, climate-smart technologies and sustainable horticultural practices are essential. In off-season farming, modern digital technologies like robotics, drones, sensors, artificial intelligence, and the Internet of Things (IoT) are enhancing crop monitoring capabilities, resource management, and production efficiency. In a similar vein, biotechnology and genetic improvement initiatives are helping to create fruit crop varieties that are high-yielding, stress-tolerant, and adaptable to shifting climate conditions (Gruda and Tanny, 2014).

Despite these impressive developments, a number of obstacles still prevent off-season fruit production technologies from being widely adopted, especially by small and marginal farmers. These obstacles include high production costs, the prevalence of pests and diseases, labour shortages, technical complexity, and environmental concerns. Therefore, increasing accessibility and successfully implementing these cutting-edge technologies require appropriate training programs, government backing, research advancements, and farmer awareness campaigns (Mishra *et al.*, 2022). By incorporating smart technologies and environmentally friendly management techniques, future off-season fruit production systems are anticipated to become more automated, precision-oriented, climate-resilient and sustainable. Environmental sustainability in horticulture will be further strengthened by the use of biodegradable materials, renewable energy systems, effective water management and integrated crop management techniques. All things considered, off-season fruit production has enormous potential to boost horticultural profitability, promote sustainable agricultural development, and enhance global food and nutritional security. The future of contemporary fruit production methods and a steady supply of fruit all year round will be greatly influenced by ongoing scientific research and technical innovation (Altieri *et al.*, 1999).

References

- Agrios, G.N. (2005). *Plant Pathology*. 5th edn. Amsterdam: Elsevier Academic Press. ISBN 9780120445653.
- Altieri, M.A. (1995). *Agroecology: The science of sustainable agriculture*. Boulder, CO: Westview Press.
- Altieri, M.A. (1999). Applying agroecology to enhance the productivity of peasant farming systems in Latin America. *Environ., Develop. Sust.*, **1**(3), 197–217.
- Castellano, S., Mugnozza G.S., Russo G., Briassoulis D., Mistriotis A., Hemming S. and Waaijenberg D. (2008). Plastic nets in agriculture: A general review of types and applications. *Appl. Engg. Agricult.*, **24**(6), 799–808. doi: 10.13031/2013.25368.
- Castilla, N. (2002). *Greenhouse technology and management*. Wallingford: CABI Publishing.
- Davenport, T.L. (2007). Reproductive physiology of mango. *Brazilian J. Plant Physiol.*, **19**(4), 363–376. doi: 10.1590/S1677-04202007000400007.
- Dent, D. (2000). *Insect Pest Management*. 2nd edn. Wallingford: CABI Publishing.
- Duckett, T., Pearson S., Blackmore S. and Grieve B. (2018). *Agricultural robotics: The future of robotic Agriculture*. UK-RAS Network White Paper.
- FAO (Food and Agriculture Organization) (2017). *The future of food and agriculture: Trends and challenges*. Rome: FAO.
- FAO (Food and Agriculture Organization) (2021). *The state of food and agriculture 2021: Making agrifood systems more resilient to shocks and stresses*. Rome: FAO. doi: 10.4060/cb4476en.
- FAO (Food and Agriculture Organization) (2022). *Climate change and horticultural crop production*. Rome: FAO.
- Fereres, E. and Soriano M.A. (2007). Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.*, **58**(2), 147–159. doi: 10.1093/jxb/erl165.
- Gaur, G.S. and Dhaliwal G.S. (2003). Protected cultivation in horticultural crops. *Indian Horticulture*, **48**(2), 8–13.
- Gebbers, R. and Adamchuk V.I. (2010). Precision agriculture and food security. *Science*, **327**(5967), 828–831. doi: 10.1126/science.1183899.
- Gill, M.S., Singh J.P. and Gangwa K.S. (2009). Integrated farming system and agriculture sustainability. *Indian J. Agron.*, **54**(2), 128–139.
- Gruda, N. and Tanny J. (2014). Protected crops – recent advances, innovative technologies and future challenges. In : *XXIX International Horticultural Congress on Horticulture: Sustaining Lives, Livelihoods and Landscapes (IHC2014)*, **1107**, 271–278.
- Hagin, J. and Lowengart A. (1996). Fertigation for minimizing environmental pollution by fertilizers. *Fert. Res.*, **43**(1–3), 5–7. doi: 10.1007/BF00747683.
- Hartmann, H.T., Kester D.E., Davies F.T. Jr. and Geneve R.L. (2011). *Plant propagation: Principles and practices*. 8th edn. Upper Saddle River, NJ: Prentice Hall.
- Howden, S.M., Soussana J.F., Tubiello F.N., Chhetri N., Dunlop M. and Meinke H. (2007). Adapting agriculture to climate change. *Proc. Nat. Acad. Sci.*, **104**(50), 19691–19696. doi: 10.1073/pnas.0701890104.
- Incrocci, L., Thompson R.B., Fernandez M.D., De Pascale S., Pardossi A., Stanghellini C. *et al.* (2020). Irrigation and fertigation management of protected crops. *Scientia*

- Horticulturae*, **264**, 109164.
- Jat, M.L., Chakraborty D., Ladha J.K., Rana D.S., Gathala M.K., McDonald A. and Gerard B. (2016). Conservation agriculture for climate-smart farming in the Indo-Gangetic Plains of South Asia. *Regional Environ. Change*, **16(6)**, 1481–1496.
- Jensen, M.H. (2002). Controlled environment agriculture in deserts, tropics and temperate regions – a world review. *Acta Horticulturae*, **578**, 19–25. doi: 10.17660/ActaHortic.2002.578.1.
- Jensen, M.H. and Malter A.J. (1995). *Protected agriculture: A global review*. World Bank Technical Paper No. 253. Washington, DC: World Bank. ISBN 0821329308.
- Jindal, K.K. and Sharma J.N. (2000). Advances in off-season vegetable and fruit production. *Acta Horticulturae*, **531**, 135–142.
- Jones, H.G. (2004). Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Exp. Bot.*, **55(407)**, 2427–2436. doi: 10.1093/jxb/eh213.
- Kader, A.A. (ed.) (2002). *Postharvest technology of horticultural crops*. 3rd edn. Oakland, CA: University of California Agriculture and Natural Resources, Publication 3311.
- Kader, A.A. and Yahia E.M. (2011). Postharvest biology of tropical and subtropical fruits. In : *Postharvest biology and technology of tropical and subtropical fruits*. Cambridge: Woodhead Publishing, pp. 79–111. doi: 10.1533/9780857093622.79.
- Kaur, R., Singh P. and Sharma A. (2023). Challenges and opportunities in protected horticulture. *Int. J. Environ. Clim. Change*, **13(11)**, 2245–2256.
- Kumar, S. and Sharma R. (2024). Recent advances in off-season fruit crop production technologies. *J. Horticult. Sci.*, **19(2)**, 115–129.
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, **304(5677)**, 1623–1627. doi: 10.1126/science.1097396.
- Langhans, R.W. and Tibbitts T.W. (eds) (1997). *Plant growth chamber handbook*. Iowa State University Special Report No. 99. Ames, IA: Iowa Agriculture and Home Economics Experiment Station.
- Liakos, K.G., Busato P., Moshou D., Pearson S. and Bochtis D. (2018). Machine learning in agriculture: A review. *Sensors*, **18(8)**, 2674. doi: 10.3390/s18082674.
- Lobell, D.B. and Gourdji S.M. (2012). The influence of climate change on global crop productivity. *Plant Physiology*, **160(4)**, 1686–1697. doi: 10.1104/pp.112.208298.
- Mishra, P.K., Sanjay K., Singh A.K., Singh H.K., Appa R.V.V., Vikas V.K. and Yadav A.L. (2022). Crop regulation in fruit crops for improving quality and income of farmers. In : *Advances in horticultural crop management*. Abingdon: Taylor & Francis, pp. 445–466.
- Monselise, S.P. and Goldschmidt E.E. (1982). Alternate bearing in fruit trees. In : Janick, J. (ed.). *Horticultural reviews*. Vol. 4. Westport, CT: AVI Publishing, pp. 128–173.
- Pal, R.N. and Lal S. (1980). Effect of pruning on growth and fruiting in guava. *Punjab Hortic. J.*, **20(1–2)**, 70–75.
- Pandey, G. and Mishra G. (2021). Role of artificial intelligence in precision horticulture. *J. Agricult. Inform.*, **12(2)**, 55–67.
- Pathak, H., Aggarwal P.K. and Singh S.D. (eds) (2012). *Climate change impact, adaptation and mitigation in agriculture: Methodology for assessment and applications*. New Delhi: Narendera Publishing House.
- Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in the United States. *Environ., Develop. Sust.*, **7(2)**, 229–252. doi: 10.1007/s10668-005-7314-2.
- Poerwanto, R., Susanto S. and Santosa E. (2008). Off-season production of tropical fruits. *Acta Horticulturae*, **772**, 127–133. doi: 10.17660/ActaHortic.2008.772.16.
- Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philos. Trans. Royal Soc. B: Biolog. Sci.*, **363(1491)**, 447–465. doi: 10.1098/rstb.2007.2163.
- Pretty, J. and Bharucha Z.P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, **114(8)**, 1571–1596. doi: 10.1093/aob/mcu205.
- Rademacher, W. (2015). Plant growth regulators: Backgrounds and uses in plant production. *Scientia Horticulturae*, **196**, 14–30.
- Rajan, R.P. and Sravani G.C. (2021). Advanced and modern fruit production techniques: A review. *The Pharma Innov. J.*, **10(7)**, 938–943.
- Resh, H.M. (2013). *Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower*. 7th edn. Boca Raton, FL: CRC Press.
- Rosenzweig, C. and Parry M.L. (1994). Potential impact of climate change on world food supply. *Nature*, **367(6459)**, 133–138. doi: 10.1038/367133a0.
- Salazar-García, S. and Vázquez-Valdivia V. (1997). Physiological perspectives of mango flowering. *Acta Horticulturae*, **455**, 180–188. doi: 10.17660/ActaHortic.1997.455.21.
- Sambo, P., Nicoletto C., Giro A., Pii Y., Valentinuzzi F., Mimmo T. *et al.* (2019). Hydroponic systems: Plan and management. *Agronomy*, **9(3)**, 119.
- Schmidhuber, J. and Tubiello F.N. (2007). Global food security under climate change. *Proc. Nat. Acad. Sci.*, **104(50)**, 19703–19708. doi: 10.1073/pnas.0701976104.
- Sethi, V.P. and Sharma S.K. (2008). Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications. *Solar Energy*, **82(9)**, 832–859. doi: 10.1016/j.solener.2008.04.003.
- Shamshiri, R.R., Jones J.W., Thorp K.R., Ahmad D., Man H.C. and Taheri S. (2018). Review of optimum temperature, humidity, and vapor pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato. *International Agrophysics*, **32(2)**, 287–302. doi: 10.1515/intag-2017-0005.

- Sharmila Bharathi, C., Pugalendhi L. and Pushpanathan K.R. (2018). Off season production of annual Moringa (*Moringa oleifera* Lam.) cv. PKM 1 through canopy management and chemical manipulation practices. *J. Pharmacog. Phytochem.*, **1**, 2218–2224.
- Singh, B. and Sirohi N.P.S. (2006). Protected cultivation of vegetables in India: Problems and future prospects. *Acta Horticulturae*, **710**, 339–342.
- Singh, G. (2001). High density planting in guava. *Acta Horticulturae*, **557**, 291–298. doi: 10.17660/ActaHortic.2001.557.39.
- Singh, R., Singh G.S. and Singh P. (2019). Protected cultivation for climate-smart horticulture. *Curr. Sci.*, **116(3)**, 345–350.
- Singh, U., Dhar S., Raghuvanshi R.S. and Roy P. (2026). Sustainable approaches for off-season production of tropical and subtropical fruit crops. *Appl. Fruit Sci.*, **68(1)**, 23–31.
- Stanghellini, C. (2014). Horticultural production in greenhouses: Efficient use of resources. *Acta Horticulturae*, **1037**, 25–36. doi: 10.17660/ActaHortic.2014.1037.1.
- Sthapit, B., Fowler M. and FAO experts (2012). *Tropical fruit tree diversity: Good practices for in situ and on-farm conservation*. Abingdon: Routledge.
- Tester, M. and Langridge P. (2010). Breeding technologies to increase crop production in a changing world. *Science*, **327(5967)**, 818–822. doi: 10.1126/science.1183700.
- Tilman, D., Cassman K.G., Matson P.A., Naylor R. and Polasky S. (2002). Agricultural sustainability and intensive production practices. *Nature*, **418(6898)**, 671–677. doi: 10.1038/nature01014.
- Tripathi, A.D., Mishra A.K., Mishra H.N. and Dubey P.K. (2020). Emerging technologies in food and horticultural crop production. *Trends Food Sci. Technol.*, **97**, 164–177. doi: 10.1016/j.tifs.2020.01.006.
- Uphoff, N. (2002). *Agroecological innovations: Increasing food production with participatory development*. London: Earthscan Publications.
- Van Henten, E.J., Hemming J., Van Tuijl B.A.J., Kornet J.G., Meuleman J., Bontsema J. and Van Os E.A. (2002). An autonomous robot for harvesting cucumbers in greenhouses. *Autonomous Robots*, **13(3)**, 241–258. doi: 10.1023/A:1020568125418.
- Van Lenteren, J.C. (2000). Success in biological control of arthropods by augmentation of natural enemies. *Biological Control*, **21(3)**, 117–128. doi: 10.1006/bcon.2000.0931.
- Vashisth, T. and Kadyampakeni D. (2020). Management options for improving flowering in citrus production. *EDIS*, **2020(6)**. Available at: <https://journals.flvc.org/edis/article/view/125145>.
- Westwood, M.N. (1993). *Temperate-zone pomology: Physiology and culture*. Portland, OR: Timber Press.
- Wheeler, T. and von Braun J. (2013). Climate change impacts on global food security. *Science*, **341(6145)**, 508–513.
- Whiley, A.W. (1993). Environmental effects on phenology and physiology of mango. *Acta Horticulturae*, **341**, 168–176.
- Winkler, A.J., Cook J.A., Kliewer W.M. and Lider L.A. (1974). *General viticulture*. Berkeley, CA: University of California Press.
- Wittwer, S.H. and Castilla N. (1995). Protected cultivation of horticultural crops worldwide. *HortTechnology*, **5(1)**, 6–23.
- Zahedi, S.M., Karimi M. and Teixeira da Silva J.A. (2020). The use of nanotechnology to increase quality and yield of fruit crops. *J. Sci. Food Agric.*, **100(1)**, 25–31.
- Zhao, C., Liu B., Piao S., Wang X., Lobell D.B., Huang Y. *et al.* (2017). Temperature increase reduces global yields of major crops. *Proc. Nat. Acad. Sci.*, **114(35)**, 9326–9331.
- Zhao, X., Carey E.E. and Wang W. (2019). Advances in greenhouse vegetable and fruit production systems. *Horticulturae*, **5(3)**, 1–16.
- Zhao, Y., Gong L., Huang Y. and Liu C. (2016). A review of key techniques of vision-based control for harvesting robots. *Comput. Elect. Agric.*, **127**, 311–323.
- Zilberman, D., Zhao J. and Heiman A. (2012). Adoption versus adaptation, with emphasis on climate change. *Annu. Rev. Resource Econ.*, **4**, 27–53.
- Zwieten, L.V., Kimber S., Morris S., Chan K.Y., Downie A., Rust J. and Cowie A. (2010). Effects of biochar from slow pyrolysis on agronomic performance and soil fertility. *Plant and Soil*, **327(1–2)**, 235–246.