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APPLE CULTIVATION IN NONTRADITIONAL AREAS: NOVEL PERSPECTIVES AND ADVANCES

A review

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ABSTRACT

Low-chilling apple genotypes have become a viable alternative for cultivation in regions with moderate to mild winters due to concerns about the impact of global climate change. Although the cultivation of low-chilling apples has been known since the last century, there is little research on their propagation and cultural operations, which creates an urgent need for structured information collection. This work presents a comprehensive review of agrotechnological practices aimed at successfully cultivating low-chilling apple cultivars in nontraditional, warmer regions in order to regulate apple prices in local markets and reduce the carbon footprint associated with transportation. By providing comprehensive insights into various agrotechnological practices and recent advances in low-chilling apple cultivation, this review can serve as a valuable resource for researchers, growers, and practitioners interested in the successful cultivation of apples in nontraditional areas throughout the globe.

Key words: chilling requirement, dormancy, low-chilling cultivars, propagation

INTRODUCTION

Apple (*Malus* × *domestica* Borkh.) is the fourth most important fruit globally after citrus, grapes, and banana which originated in Central Asia (Kazakhstan, Kyrgyzstan, China, and Kashmir) over 4000 years ago (Fotirić Akšić et al. 2022). Apple is being cultivated since time immemorial and its cultivation is not new to the Indian subcontinent. The overall worldwide apple demand during 2020–2024 is headed to enhance by 3.42 million tonnes (MT) at a mean annual growth rate of over 1% (Raj et al. 2021). The pome is a source minerals, dietary fibers, carbohydrates, and bioactive compounds, like vitamin C and antioxidants. Nowadays, apple plays an integral part in the prescription of nutritionists and dieticians. Apple usually grows in areas where winters are cold, springs are frost-free, and summers are mild. There are over 7500 known apple cultivars. They are classified based on their chilling requirements into low, medium, and high-chilling cultivars (Hawerroth et al. 2013; Pramanick et al. 2017). Chilling requirements are mainly expressed in chilling hours (CHs), which is the minimum time (h) required for apple trees to remain below 7.2°C during the dormant period. Most apple cultivars require 1000–1600 CHs during winter to break the resting period, however, some low-chilling apple cultivars require only 500–800 winter CHs (El-Agamy et al. 2001a; Labuschagné et al. 2002). The calculation of chilling units (CU) for apple cultivation is critical for ensuring adequate dormancy and subsequent productivity. Chilling hours were calculated as per Weinberger (1950) model which counts each hour from 0 and 7.2°C as one chilling hour (Kaufmann & Blanke 2019).

Currently, apple production is mainly restricted to temperate regions worldwide; as the most marketable apple cultivars have medium to high chilling hour requirements and fail to produce in warm regions. The leading apple producer in terms of product mass and area is China (Fig. 1), accounting for about half of the total world production (FAO 2020). Apples are also grown in several African regions, although production is generally small

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compared to other parts of the world. Some of the leading apple-growing regions in Africa include the Western Cape, Eastern Cape, and the Langkloof Valley of South Africa, the Middle Atlas Mountains region of Morocco, the northern regions of Algeria, the Cap Bon peninsula of Tunisia, the Nile Delta in Egypt, and the highland regions of Ethiopia (Admasu et al. 2022). India produces 2.27 MT from 0.31 million hectares (Mha). In India, apple production is mainly concentrated in the hilly regions of the northwestern parts – Jammu and Kashmir, Himachal Pradesh, and Uttarakhand. However, on a marginal scale, apples are also grown in some Northeastern Indian states like Arunachal Pradesh, Nagaland, Sikkim, Meghalaya, and Manipur (Anonymous 2018).

Global climate change is altering the phenology of deciduous plants, including apple trees. This is of concern in regions where apples are produced commercially, as they are expected to become unsuitable for conventional cultivars (Legave et al. 2015). These disturbances forced scientific community to introduce low-low-chilling apple cultivars that will yield well in moderately warm and mild winter climatic conditions. They can be more resistant to climatic and environmental changes, which will allow for an increase in the area of apple cultivation. The mountainous terrains of various regions (Castro et al. 2015, 2016; Mditshwa et al. 2016; Raj et al. 2021; Yirgu et al. 2021), having moderately temperate to subtropical climatic conditions, provide enough chilling hours for the breakdown of endodormancy (Rodríguez-Arzuaga et al 2019).

Transportation plays a crucial role in moving agricultural commodities such as inputs, crop products, and planting material to markets. However, transporting these goods to new, nontraditional regions requires a lot of fuel, ultimately increasing the carbon footprint. Furthermore, globally, transport alone contributes 14% of total greenhouse gas emissions (IPCC 2014). The introduction of cultivars capable of adapting to nontraditional regions allows for regulation of the price of the commodity on the local market and reduces the carbon footprint.

Cogitating the consequences of global warming on apple production and extending its production in nontraditional warmer regions, the current review is envisaged to highlight the importance of low-chilling apple cultivars as an alternative choice over conventional ones where winter is moderate to mild warm. To successfully cultivate low-chilling apples, comprehensive information about their genotypes is needed. Therefore, the article intends to collate the available good agrotechnological practices adopted for low-chilling apple cultivars cultivation throughout the world.

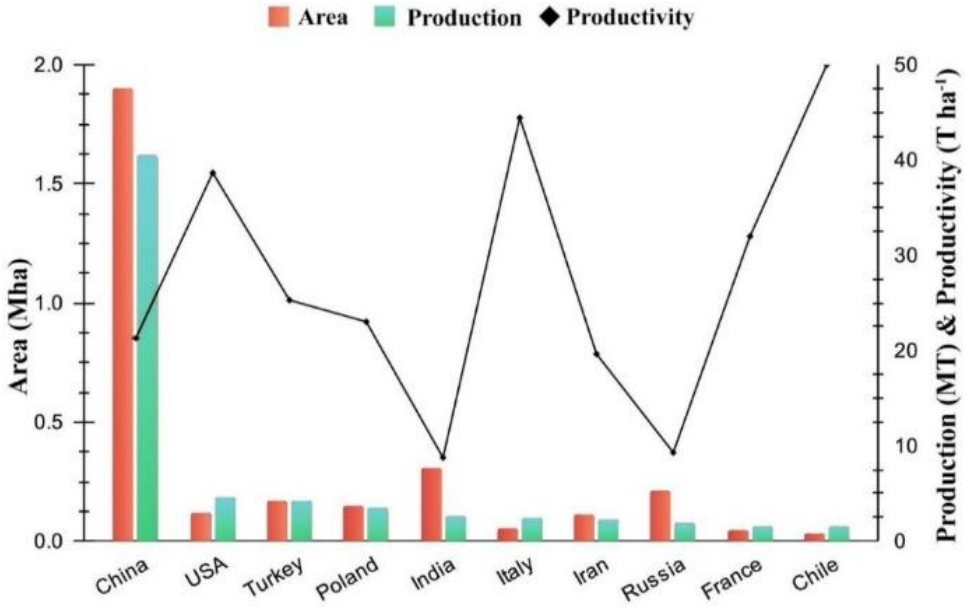


Figure 1. Leading apple producing countries in the world

CULTIVARS AND ROOTSTOCKS

Breeders developed cultivars requiring low-chilling hours, such as 'Anna' and 'Dorsett Golden', which needs only <300 chilling hours to flower for cultivation in warmer regions (Hauagge & Cummins 1991). Among different apple cultivars, 'Dorsett Golden' ('Golden Delicious'), 'Eva' ('IAPAR 75'), 'Princesa' ('NJ56' × 'Anna'), 'Fuji' ('Red Delicious' × 'Ralls Janet'), 'Caricia' ('IAPAR 77'), and 'Anna' ('Red Hadassiya' × 'Golden Delicious') have been grown (Table 1) successfully in low-chilling regions of Argentina, Brazil and India (Pommer & Barbosa 2009; Castro et al. 2015; Raj et al. 2021). In Peru, crab apple rootstock *Malus sylvestris* Mill. is reported to be a better alternative to quince rootstock for the scion grafting of 'Anna' and 'Dorsett Golden' (Bederski 1988). In commercial apple orchards grown under warm conditions, most growers have adopted the Malling series of rootstocks for grafting apple cultivars requiring low-chilling units (Castro et al. 2016; Foster et al. 2017). Most rootstocks of the Malling series had short stature and a less vigorous nature. Therefore, the canopy of low-chilling cultivars is mostly less vigorous than conventional cultivars. The 'Anna' cultivar planted on 'MM106' showed dwarfing habit, early bearing, and higher fruit set with 3 or 4 fruits per cluster; however, the size of fruits is small. The cultivar 'Dorsett Golden' showed vigorous habit in the initial years when planted on 'MM106', with fruits on terminal buds of water sprouts. However, the growth habit ceased with fruiting on spurs in the latter years, owing to an increased number of fruits that used up food reserve. In Brazil, the low-chilling cultivars 'Eva' and 'Caricia' were successfully grafted onto 'M9' rootstock (Castro et al. 2015), which is most widely accepted and characterized best among dwarfing apple rootstocks during the last century (Hatton 1917); however, 'Caricia', 'Eva', and 'Princesa' were grafted on 'MM111' in Argentina (Castro et al. 2016). Cleft-grafting of a 'Royal Gala' scion was successfully performed onto 'M9' (clone 'NZ9'), 'M27', and 'M793' (one-year) rootstocks in New Zealand (Foster et al. 2017). The research was carried out by Sharma et al. (2004) in India by growing various low-chilling apple cultivars, namely: 'Tropical Beauty', 'Tamma', 'Shlomit', 'Red June', 'Red Baron', 'Parlin's Beauty', 'Michal', 'Maayan', 'Early McIntosh', 'Chahla', 'Aziza', and 'Anna'. Among all cultivars under investigation, 'Tropical Beauty' performed best in the cultivars under study in the lower Himalayan region. Low-chilling apple cultivars differed in their characteristics (Table 1); therefore, better yield quality could only be achieved by using compatible rootstocks with the desired properties (Pommer & Barbosa 2009).

Table 1. Description of low-chilling apple cultivars

Cultivar	Country of origin and year	Characteristics
'Anna'	Israel 1967 (Abdel-Sattar & Kotb 2021)	Chilling requirement of 300 hours. Crisp texture at harvest and soften rapidly, high amount of ethylene (Klein & Lurie 1990; Nautiyal et al. 2020).
'Dorsett Golden'	Bahamas 1953 (Miller & Sherman 1980)	Color from pale to light yellow with a pinkish or light red flush, very sweet taste, semi-spreading and semi-spur-type bearing habit, resistance to powdery mildew (Miller & Baker 1982; Sarkhosh et al. 2019).
'Fuji'	Japan 1930 (Sadamori et al. 1955)	Watercore rich fruits, susceptibility to physiological disorders i.e. browning and breakdown during storage (Tanaka et al. 2020).
'IAPAR 75' 'Eva'	Brazil 1995 (Hauagge & Cummins 2000)	Heavy set on terminals, spurs and lateral buds of 1 year old, susceptibility to scab, canker, and Marssonina leaf spot (Hauagge 2010).
'IPR Julieta'	Brazil 1995 (Hauagge & Cummins 2000)	Performs effectively in regions with 100–500 chill units, resistant to the necrotic leaf blotch. Red strips on fruits surface (30–50%), sweet and juicy, with a delicate texture and moderately vigorous with open canopy (Hauagge 2010).
'Tropic Sweet'	USA 1995 (Andersen et al 2022)	Fruit is sweeter (14–15° Brix) and firmer than 'Anna' fruit, but less red and acidic, has a 30 percent red blush, and is susceptible to skin rust. Trees are semi-spreading and of medium height (Andersen et al 2022).
'SCS443 Isadora'	Brazil 2001 (Denardi et al 2023)	Fruits have a red peel and firm flesh, with a high sugar content (14.5%) and a very crunchy and juicy texture, great storage ability in postharvest (Denardi et al 2023).
'Pink Lady'	Australia 1973 (Cripps et al. 1993)	Greenish yellow (30–60%) surface along with pinkish red solid (40–70%), Resistance to bitter pit and slight susceptibility towards powdery mildew (Cripps et al. 1993)

BOTANICAL CHARACTERISTICS AND CLIMATIC REQUIREMENTS

Dormancy

Most deciduous fruit trees require proper chilling hours to achieve optimal bud burst or flowering. Because the chilling period in tropical or subtropical regions is short, there are not enough chilling hours to form buds, further delaying the opening of apple flower buds. Vegetative buds, as well as reproductive buds, are susceptible to late chilling, which exposes them to physiological defects and also destabilizes the dormant period in the following season. In Peru, the chilling requirement of low-chilling apple orchards was regulated by promoting dormancy release or preventing true dormancy (Bederski 1988). The methods used were topping and bending branches in summer, hand defoliation, and artificial drought. In fully fruiting orchards, defoliation is carried out with 10% urea at the end of the drought span, and dormancy breaking spray with 0.1% a.i., dinitro-*ortho*-cresol + 4% emulsified mineral oil after the first irrigation. A study conducted by Wang and Faust (1994) reported the release of dormancy in the flower buds of low-chilling apples with changing polyamine content. Hydrogen cyanamide (49%) has been reported to regulate the nitrogen and polyamine content in buds, effectively breaking bud dormancy in low-chilling apple cultivars (El-Yazal & Rady 2012). Hauagge and Cummins (2000) observed a correlation between chilling unit accumulation and bud break of apples. With increasing amounts of chilling accumulation, bud break also inclines by 32.6% and 52.6% in 'Anna' and 'Dorsett Golden' cultivars, respectively, during 1994–1996 (El-Agamy et al. 2001b). The cultivar 'Anna' needed a few days more to reach full bloom and fruit set over 'Dorsett Golden', whereas it reached fruit maturity earlier than 'Dorsett Golden' (El-Agamy et al. 2001b). The *MdDAM1* and *MdDAM4* gene silencing are known to regulate bud dormancy by retarding growth. Moser et al. (2020) observed that *MdDAM1* gene expression declined drastically in January and was completely silenced in February in the low-chilling apple cultivars 'Anna' and 'Dorsett Golden', one month before 'Golden Delicious' (a high-chilling cultivar). *MdDAM1* gene expression showed a strong correlation with bud break. The variation in *MdDAM1* gene expression between conventional and low-chilling cultivars might result from single nucleotide mutation in the cultivars 'Dorsett Golden' and 'Anna', which causes early bud break under low-chilling cultivars. Therefore, it will be necessary to consider switching to low-chilling cultivars rather than conventional ones for early bud break.

Pollination behavior

The apples belong to the Rosaceae family, and most cultivar flowers are bisexual and epigynous. (Kraus & Ralston 1916; Dennis 2003; Rieger 2006). Most apple cultivars are self-incompatible, which hampers inbreeding (Dennis 1979; Westwood 1993), and fruit set is therefore, dependent on cross-pollination (Ramirez & Davenport 2013). Pollination in 'Anna' depends mainly on the insect population in the Colombian region (Botero Garcés & Morales Soto 2000); however, some studies support its self-compatibility to some extent (Petri 1993). A significant characteristic of the 'Anna' cultivar is flowering buds on the lateral part of shoots, indicating a prolific and precocious nature. 'Anna' and 'Granny Smith' are commonly cross-pollinated with 'Dorsett Golden', a well-known pollen-producing cultivar in South America (Schwarz 1994). In the highland tropics of Colombia, the low-chilling 'Dorsett Golden' was planted for pollination of the 'Anna' at a ratio of 1 : 8 (Casierra-Posada 2012). According to pollination studies conducted by Guevara (1992) in the Aserrí canton in the San José province of Costa Rica, 'Anna' was found to be a self-compatible cultivar. Other studies reported a high level of autogamy (7%) of 'Anna' (Díaz 1993) which means they are well-acclimated to cross-pollination (Petri 1993). 'Golden Delicious' seedlings flowered at 42.1% in the second year, while some 'Anna' crosses at 85% (Labuschagné et al. 2002). 'Anna' seedlings flowered at a very early growth stage and were highly reproductive, revealing precocity in their nature resilient to the local environment, which benefits low-chilling apple cultivar (Labuschagné et al. 2002).

Climate and topography

Apple trees can be grown at 1100–2300 m from sea level in numerous tropical and subtropical areas (Erez 2000; Bekele-Tesemma 2007; Raj et al. 2021;

Argenta et al. 2022). The Eastern and Western Himalayan regions of India are well known for low-chilling apple production with altitudes of 1300–1500 m and maximum and minimum temperatures of 26–30°C and 19–22°C, respectively, and an annual rainfall of 2000–2500 mm during the growing period (January–August) (Raj et al. 2021). Similarly, well-grown low-chilling apple cultivars are grown in orchards in Grabouw, South Africa (34°12'12" S, 19°02'35" E) at an altitude of about 350 m above sea level, in a warm-summer Mediterranean climate (Mditshwa et al. 2016). High adaptability and optimal productivity make low-chilling apple cultivation widespread in Latin America, India, the Middle East, and parts of Africa (Mohamed 2008; Pommer & Barbosa 2009; Castro et al. 2016).

PROPAGATION

Apple propagation is mainly done by grafting or layering using scions and selected rootstocks. Due to several disadvantages associated with traditional propagation, *in vitro* propagation procedures for apple rootstocks have been developed (Petri et al. 2019). Gaudie et al. (2016) developed a complete micropropagation protocol for the 'Anna' and 'MM106' genotypes, adapted to the climatic conditions of Ethiopia.

LAYOUT AND SPACING

The orchard layout should ensure equal and proper sunlight during the daytime. Therefore, rows of trees should be oriented north-south, not east-west (Jung & Choi 2010). Under uniform terrain, trees raised on dwarfing or semi-dwarfing rootstocks should be planted in a rectangular system where the distance between rows is approximately 0.5 m wider than the row tree spacing. Mountainous topographical features should be done on the terraces (Anonymous 2022). The spacing and plant population per unit area rely on the scion-rootstock combination, soil fertility status, and system of training adopted for the plant. The low-chilling apple cultivars were planted at 5 m × 5 m in silt loam soils in the Western Himalayan region of India (Raj et al. 2021) and 4 m × 4 m under sandy soil in Egypt (Nagy 2018). A study conducted by Finetto and Ward (1990) reported better compatibility of rootstocks 'MM106' and 'MM111' with 'Ein Shemer' (low-chilling cultivar) with tree spacing 4 m × 6 m whereas the cultivar 'Dorsett Golden' suited with 'MM106' at spacing 5 m × 5 m. In South Africa (Grabouw), the low-chilling apple 'Fuji' cultivar was grafted onto rootstock and planted with spacing 4 × 1.5 meters, giving a total of 1667 trees per hectare (Siboza et al. 2020). A commercial orchard in Santa Fe (Argentina) planted a low-chilling apple 'Eva' and 'Caricia' cultivars at 4 m × 2 m spacing (1250 trees per ha), trained as a horizontal palmette system with an east-west orientation (Castro et al. 2016). The efficacy of the high-density planting (HDP) orchards is mainly associated with light interception efficiency.

INTERCULTURAL PRACTICES

Agricultural management strategies regarding fertilization, weed management, crop load, and irrigation are considered to be the main determinant of orchard yield and fruit quality in different regions (Table 2). Under semi-arid climatic conditions in Yemen, low-chilling apple cultivars ('Ein Shemer' and 'Dorsett Golden') are irrigated using the bubbler and basin system. The weekly application of water was done during the period of highest evapotranspiration (May/June); however, the application interval was extended (every 10 days) from July-October and January–May (Finetto & Ward 1990). Optimal irrigation in low-chilling apple cultivars during autumn was reported to favorably impact the nutrient content and yield (Abdel-Sattar & Kotb 2021). The time and duration of irrigation differ according to the climatic conditions of the region and the phenological phases of the trees (Williams et al. 1985). Abdel-Sattar and Kotb (2021) reported that controlled irrigation during noncritical periods (autumn), is an effective technique to improve bud formation and enhance fruiting spurs and production of 'Anna'.

Table 2. Cultural and management practices in apple

Cultural practices	Country	Reference
Crop load management		
Summer pruning reduces vegetative growth and bitter pit incidence in apple tree along with enhance hue of apple skin.	Spain	Guerra et al. (2021)
Application of ammonium thiosulfate at a concentration of 2.5% as a blossom thinner has been shown to be effective in improving fruit quality and reducing crop load.	Brazil	Marchioretto et al. (2018)
Single or twice application of Metamitron at 1.65 kg·ha^{-1} at different fruit size found to reduce number of fruits per tree and significantly improved average fruit weight, color and diameter.	Spain	Gonzalez et al. (2020)
Mulching		
Short exposure to reflective mulch (at least two weeks) was sufficient to improve the flush coloration of the outer, inner and underside of apple fruits.	New Zealand	Funke and Blanke (2021)
Soil mulching with polyethylene enhanced vegetative and reproductive growth. The fruit number, size, length and weight significantly increased with black polyethylene mulch.	Egypt	Aly et al. (2018)
Living mulches such as *Mentha piperita* (peppermint), *Fragaria vesca* (wild strawberry), and *Tropaeolum majus* (nasturtium) effectively suppressed weed growth in organic apple orchards. This underscores their potential as a practical method of soil management and weed control in organic farming.	Poland	Golian et al. (2023)

Aly et al. (2018) reported that soil mulching with mainly black polyethylene enhanced the vegetative and reproductive growth of low-chilling 'Anna'. Fruit thinning enabled enhancement of fruit size and increased bloom and yield in the next season (Yuan 2007). Shoot bending stimulated flower bud initiation (spurs) on the branches and reduced the plant vigor, which further increased the potential yield of 'Dorsett Golden' (Petri & Stuker 1988; Finetto & Ward 1990). Among different training systems, the open center system was adopted in Peru in 'Ein Shemer' on 'MM106' and 'MM111', whereas 'Dorsett Golden' planted on 'MM106' were trained in the spindle bush system (Finetto & Ward 1990).

FERTILIZATION

Mineral nutrition is closely related to the quality of apples. For example, application of above-optimal N rates was reported to reduce fruit color and firmness of 'Gala' apple (Neilsen et al. 2000). The standard fertilization program for Peruvian apple orchards includes 15 tons of manure per hectare per year plus 500–800 kg of nitrogen per hectare, using a fertilizer N : P : K : Mg ratio of 1 : ¼ : 1 : ¼. For the low-chilling cultivar 'Anna', which is particularly susceptible to zinc deficiency, 2–4 foliar sprays of Zn are required per year (Bederski 1988). For low-chilling apple cultivars the primary concern remains bitter pit, while in temperate regions, senescent breakdown due to calcium deficiency is a major concern (Bramlage et al. 1980).

DISEASES AND PEST PROTECTION

There is a dearth in the literature in the context of pest and disease management of low-chilling apple cultivars. Beetles, leafhoppers, aphids, mites, maggots, and thrips attack apple trees to lay their eggs and start feeding. These pests induce spots or holes in fruits and damage leaves, leading to early fruit drop. Additionally, curling and yellowing of plant leaves, skeletonization, and defoliation are more common symptoms of pest attack (Wagner et al. 1991). Orchards are further susceptible to various viral, fungal, and bacterial diseases. Rani et al. (2022) isolated RNA from 24 diseased leaf samples from low-chilling apple cultivars ('Anna' and 'Dorsett Golden'), which were found positive for *Apple stem grooving virus* (ASGV) *and Apple scar skin viroid* (ASSVd). Walia et al. (2015) postulated the spread of ASSVd through whiteflies and grafting. Generally, the low-chilling apple cultivars are harvested during the second fortnight of June. The maturing period of low-chilling apples coincides with the severe outbreak of wasps, possibly due to higher temperatures and lower humidity. Although wasps are well-known beneficial predators, as they prey on other insects that feed on plants, a severe wasp attack was observed on the apples of low-chilling cultivars. Apple fruits are more susceptible to insect attacks because they are an easy source of food. The infested fruits lose their aesthetic value, which leads to economic loss for the growers.

Preliminary trials to halt the attack of wasps conducted by CSIR-IHBT by using various organic preparations, among which, the most effective results were observed with fermented honey solution trap (unpublished data). Fungal diseases significantly impact low-chilling apple cultivars, particularly in central Argentina regions where *Colletotrichum siamense* has been identified as the primary agent causing bitter rot and leaf spot (Fernandez et al. 2022). The 'Anna' is susceptible to several fungal diseases, primarily apple scab (*Venturia inaequalis*) and powdery mildew (*Podosphaera leucotricha*). Research indicates that effective management of these diseases often involves the use of chemical fungicides, such as carbendazim and captan, which have shown efficacy in reducing infections and improving fruit quality (Abo Ogiela & El-Shoraky 2020). Nonchemical control methods for apple diseases have gained traction as sustainable alternatives to chemical fungicides. Research highlights several effective strategies. For instance, sanitation practices such as collecting fallen leaves and mulching have significantly reduced apple scab incidence while enhancing fruit yield and economic returns in both integrated and organic management systems (Antal et al. 2024). Furthermore, formulations based on mycoendophytes like *Trichoderma longibrachiatum* have effective in controlling apple scab and Valsa canker, showcasing a reduction in disease incidence (Bensaci et al. 2022).

Protection of apples against storage diseases

Low-chilling apple cultivars are particularly susceptible to various storage diseases, which can significantly impact their postharvest quality and marketability. Research indicates that these cultivars often experience physiological disorders due to inadequate chilling hours, increasing susceptibility to pathogens during storage and making them more vulnerable to diseases such as blue mold and soft rot (Hauagge 2010; Vittani et al. 2023). Low oxygen pre-storage treatment significantly decreases chilling injuries such as superficial scald in low-chilling apple types. It prevents storage diseases by lowering ethylene and oxidation products during cold storage (Pesis et al. 2014). Biocontrol agents such as the psychrotrophic yeast *Leucosporidium scottii* have shown promise in managing postharvest diseases by producing antifungal substances and forming biofilms, which enhance their effectiveness (Vero et al. 2013). Previous research has shown that apples heat treated in water at 40–50 °C for 20–90 minutes and then stored at a low temperature of 2 °C for 24 hours have improved postharvest quality and are suitable for minimal processing. In conclusion, mild heat treatments can improve the quality and bioactive content of fresh-cut low-chilling apples (Rodríguez-Arzuaga et al. 2019).

Postharvest management (diseases and disorders during storage)

The shelf-life of fruit is critical in determining both its quality and profitability. Around 1 trillion US dollars are lost annually globally due to waste caused by inefficient postharvest management practices (Gustavsson et al. 2011). Generally, low-chilling apple cultivars ('Anna' and 'Dorsett Golden') are harvested from the end of June to the start of July. Most of these fruits are supplied to the markets for fresh consumption, but prices are sometimes low during that period. The shelf life of low-chilling apple cultivars is considered to be short (Stander et al. 2021). The combined application of chitosan and salicylic acid on fruits after harvest helped to mitigate the incidence of decay, reducing weight loss, electrolyte leakage, and retarding the loss of firmness, besides keeping other physicochemical characteristics, thus enhancing the storage and poststorage shelf life of low-chilling apple cultivars (Ahmed et al. 2022). Various diseases and disorders can significantly impact fruit quality and marketability during storage. Therefore effective pre-storage treatments, proper storage conditions, and controlled atmosphere storage chambers are essential to minimize losses and maintain apple quality (Khadiri et al. 2024). Low oxygen storage can prevent superficial scald, a chilling injury disorder, by promoting specific metabolic responses and gene expression changes in apples (Populin et al. 2023). In addition, cold storage of the harvested crop ensures the supply quality apples during the off-season and helps to obtain a reasonable market price in the middle and low mountain areas (Mitropoulos & Lambrinos 2000).

The low temperature, high humidity, and gas exchange through air circulation slow respiration and ethylene production as much as possible under controlled conditions (Paul & Pandey 2014).

CSIR-IHBT INITIATIVE FOR APPLE CULTIVATION IN NORTH-EASTERN INDIA

A novel effort was initiated to cultivate apples in the northeastern states of India. The attempt was made with two sets of cultivars which require low-chilling hours (300–500) in the Champhai district of Mizoram by CSIR-IHBT, to lower the price of imported apples in the local market. The first set comprised 'Anna' and 'Dorsett Golden', whose chilling requirements were under 300 hours, and the next set comprised 'Gala' and 'Fuji', whose chilling requirements were around 500 hours per season (Anonymous 2018). Subsequently, in 2016, a preliminary trial was carried out by planting seven low-chilling apple cultivars, namely: 'Gale Gala', 'Red Lum Gala', 'Sun Fuji', 'Early Fuji', 'Red Fuji', 'Anna', and the pollinator cultivar 'Scarlett Gala' in the Champhai District of Mizoram state in northeastern India, covering about 2.1 hectares. Another attempt was made to introduce low-chilling apple in the Ukhrul region (Manipur) and West Khasi region (Meghalaya) of Northeast India by CSIR-IHBT in alliance with the North Eastern Region Community Resource Management Project (NERCORMP). Similarly, as part of a public consultation exercise in mid-2020, CSIR-IHBT planted around 25,000 low-chilling apple genotypes across 22 hectares in Meghalaya and Arunachal Pradesh. The cultivars introduced were: 'Scarlett Gala', 'Early Fuji', 'Sun Fuji', 'Gale Gala', 'Pink Lady', 'Granny Smith', 'Red Fuji', 'Dorsett Golden', and 'Anna'. Following the introduction of low-chilling apple cultivars in Mizoram by CSIR-IHBT in 2016, the area under cultivation has increased by about 63 hectares by 2024 in Mizoram, Manipur, Meghalaya, and Arunachal Pradesh (unpublished data).

PHYTOCONSTITUENTS AND THEIR HEALTH BENEFITS

Nutritive qualities including a high content of vitamins, pectin, organic acids, minerals, dietary fibers, carotenoids, and carbohydrates are making apples highly appreciated by consumers (Fotirić Akšić et al. 2020; Wicklund et al. 2021). Navarro et al. (2018) identified 36 phytochemical compounds from the skin and flesh of 'Anna' cultivars including flavan-3-ols monomers, flavan-3-ol gallates, catechin, epicatechin, phloretin, 3-hydroxyphloretin derivatives, procyanidin (A-type dimers, B-type pentamers, B-type tetramer, B-type trimers, and B-type dimers), flavonoids, phenolic acids, and vomifoliol derivatives. Many of these compounds exhibit high antioxidant activity (Table 3), and thus can reduce cardiovascular disease, cancer, asthma, diabetes, obesity, and Alzheimer's disease (Hyson 2011; Ferretti et al. 2014). A study conducted in the lowlands of the Himalayas revealed the presence of essential amino acids (valine, tyrosine, lysine, threonine, aspartate, arginine, and histidine) and polyphenolic compounds (cinnamic, gallic, and caffeic acids) in the 'Anna', 'Dorsett Golden' and other low-chilling cultivars (Raj et al. 2021). Apple samples from north-eastern India were examined for their quality attributes and compared simultaneously with traditional apple cultivars whose maturity overlaps with low-chilling apple cultivars. Apples grown in Mizoram have been shown to have higher contents of total sugar, sucrose, fructose, and glucose compared to traditional cultivars (Raj et al. 2021). The known mycotoxin, patulin, released by *Penicillium* species, is commonly found in spoiled apples or derived products, pies, juices, and preserves (Moretti & Sarrocco 2016). Research conducted by Amra et al. (2009) showed that 60% of the 'Anna' fruit contained patulin ranging from 1.5 to 155 ppb, whereas for 'Dorsett Golden' 40% of the fruit had concentrations from 0.6 to 62 ppb. Patulin is considered genotoxic, but its carcinogenic potential has not yet been demonstrated.

Table 3. Different phytochemical compounds and their potential benefits in apple

Chemical compound	Properties	Reference
quercetin	antidiabetic, antiinflammatory, antioxidant	Chitkara et al. (2012); Salehi et al. (2020)
catechin	anti-inflammatory, antimutagenic, anticarcinogenic	Biasi et al. (2011)
phloridzin	antidiabetic, antioxidant, antiaging	Ehrenkranz et al. (2005); Sun et al. (2017); Prabhakar et al. (2020)
rutin	significant reduction in tumor size, neuroprotective effect, anticonvulsant activity	Khan et al. (2009); Lin et al. (2012); Nieoczym et al. (2014)
chlorogenic acid	antidiabetic, antiobesity, antioxidant	Santana-Gálvez et al. (2017)
hyperin	regulate immune function, analgesia, avoiding microthrombosis	Ping (2020)
procyanidin B_2	protect against diet induced obesity, nonalcoholic fatty liver disease	Xing et al. (2019)

CONCLUSION

Growing demand along with climate change has forced growers to cultivate lower chilling apple cultivars. The success of their cultivation in South America, Asia, and Africa has contributed to increased local apple production, reducing the need for imports. It is assumed that by 2030, due to climate trends, mainly low-chilling apple cultivars will yield, and a transition from conventional to low-chilling cultivars can be expected. Among all the low-chilling apple cultivars, 'Anna' and 'Dorsett Golden' were found to have high adaptability and optimum productivity, thereby spreading all over the globe. Several antioxidant compounds have been observed in low-chilling apples, but pests and diseases will continue to be a problem requiring more intensive investigations.

Author's contribution

Praveen Thakur and Ayush Paul searched and compiled the literature and wrote the manuscript; Yog Raj prepared and revised the manuscript; Rakesh Kumar conceptualized manuscript and finalized the draft.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the present paper.

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