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SUMMER PRUNING IN APPLE (*Malus domestica* borkh.): PHYSIOLOGICAL BASIS, TECHNIQUES AND FRUIT QUALITY OUTCOMES: A COMPREHENSIVE REVIEW

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ABSTRACT

Apple (*Malus domestica* Borkh.) is one of the most important temperate fruit crops, cultivated between 25 and 52 degrees latitude (Rehman *et al*., 2021). Summer pruning, defined as the selective removal or modification of shoots and branches during the active growing season, is a multifunctional canopy management practice that reduces vegetative competition, improves light penetration into the bearing zone, re-exposes spur leaves and fruit to sunlight, concentrates fruit maturation, and simultaneously enhances productivity and fruit quality while reducing fungal disease pressure (Rom and Ferree, 1984; Autio and Greene, 1990). This review synthesises global and Indian research to assess the mechanistic basis, principal techniques, and documented effects of summer pruning on tree vigour, flower bud formation, fruit quality, and disease management, with special attention to the temperate Himalayan apple belt of India. Summer pruning modifies carbohydrate partitioning, cytokinin-to-gibberellin ratios, and light distribution within the canopy, collectively stimulating flower bud differentiation and improving anthocyanin biosynthesis in fruit. Evidence from Dr. Y.S. Parmar University of Horticulture and Forestry, Nauni, KVK Kinnaur (Himachal Pradesh), and Kulgam (Jammu and Kashmir) confirms that well-timed, moderate summer pruning consistently improves fruit colour, reduces physiological storage disorders including bitter pit, and complements dormant pruning in high-density plantings on clonal rootstocks. Altitude-specific timing guidelines for Himalayan orchards and priority research gaps are identified.

Keywords **:** Apple, Canopy management, Flower bud differentiation, Fruit quality, Himalayan orchards, Humic acid, Summer pruning, Temperate horticulture.

Introduction

Apple is among the most important temperate fruit crops consumed worldwide, with its cultivation sites falling geographically between 25 and 52 degrees latitude (Rehman *et al*., 2021). Jammu and Kashmir is the leading apple-producing state in India, and the village of Kotgarh in Shimla district, Himachal Pradesh, is widely regarded as the apple bowl of India. The Shopian region of Jammu and Kashmir is known as the apple bowl of Kashmir and produces approximately two million tonnes of apples per year (Rehman *et al*., 2021). Globally, apple cultivation covers approximately five million hectares and produces more than 95 million tonnes annually (FAO, 2023), generating a gross product of nearly USD 50 billion annually. China accounts for nearly 50% of global production, yet its average yield of 22.3 t ha^{-1} remains substantially below the 33 to 51 t ha^{-1} achieved by France, Italy, and Chile (Qiu *et al*., 2025), reflecting underutilisation of advanced orchard management technologies including summer pruning.

Apple productivity depends on canopy management, scion and rootstock behaviour, fertilisation, disease control measures, and nutrigation, and among all these factors canopy management techniques play a vital role in the production function

(Rehman *et al*., 2021). In India, apple cultivation is concentrated in Jammu and Kashmir (approximately 74% of national production) and Himachal Pradesh (approximately 18 to 26%), with smaller contributions from Uttarakhand (NHB, 2018). India's average apple productivity is approximately 8.2 t ha^{-1} (FAOSTAT, 2022), far below international benchmarks. Himachal Pradesh's apple economy generates revenues exceeding INR 5,000 crore annually and constitutes approximately five percent of the state's gross domestic product (Kumar, 2025). The transition to high-density and ultra-high-density plantings (HDP and UHDP) on clonal dwarfing rootstocks including M.9, M.26, and MM.106 has created complex canopy management demands across the Himalayan landscape (Rehman *et al*., 2024).

There are two pruning operations made in apple: dormancy period pruning and summer pruning (Rehman *et al*., 2021). Dormant pruning involves removal of dead, defunct, and diseased branches and heading back of terminal ends of shoots, is an invigorating process, and is performed after harvest in late winter (Utermark, 1977; Rehman *et al*., 2021). Summer pruning is performed in the active season and is limited to removal of upright growing and vigorously growing current season shoots, primarily to reduce excessive vegetative growth, balance vegetative and reproductive growth, and activate sleeping buds to increase the number of spurs per branch (Rehman *et al*., 2021). Summer pruning has been regarded as less invigorating than dormant pruning (Utermark, 1977), and pruning intensity, time, and method have varying effects on apple quality at harvest and during storage (Wertheim, 2005).

Summer pruning has been reported to reduce vegetative growth, improve canopy light penetration, re-expose spur leaves and fruits of the interior canopy, enhance fruit quality, concentrate fruit maturation, and increase the number of flower buds (Rom and Ferree, 1984). It helps maintain an optimum carbon-to-nitrogen (C: N) ratio, crucial for apple development, and is mainly suitable for trees trained as restricted forms including cordon, espalier, fan, pyramid, and spindle bush; trees grown as standards or bushes are managed primarily with winter pruning (Rehman *et al*., 2021).

Global Apple Production and the Himalayan Orchard Context

Global apple production has been transformed by the adoption of HDP and UHDP systems using fully dwarfing clonal rootstocks, which make active in-season canopy management essential, as canopy density accrues rapidly and interior light depletion becomes the primary constraint on fruit quality and spur productivity (Gandev and Dzhuvinov, 2014; Bhusal *et al*., 2017). Summer pruning is more critical in HDP systems than in traditional low-density orchards because the compact tree architecture provides little natural openness to interior light. The relevance of this distinction for Indian orchardists is significant: traditional low-density orchards in Kinnaur and other Himalayan districts predominantly consist of large-framed trees on vigorous seedling rootstocks for which summer pruning is less effective, whereas the rapidly expanding HDP systems on M.9, M.26, and MM.106 are precisely the restricted, compact-trained forms that benefit most from systematic summer pruning (Kumar, 2025; Rehman *et al*., 2021).

In the Indian Himalayan belt, the YSP UHF HP-HDP World Bank Project demonstrated that high-density plantings using M.9 and MM.106 rootstocks can achieve productivities of 36 to 45 t ha^{-1} for varieties including Jeromine, Red Cap Valtod, Scarlet Spur II, and Redlum Gala at Nauni after five years. Kinnaur district, situated in the cold dry trans-Himalayan zone at 1,500 to 3,500 m above mean sea level, represents the premium segment of Himachal Pradesh's apple economy. Traditional orchards on vigorous seedling rootstocks still predominate, with current productivity estimated at approximately 35 boxes of 20 kg per bigha, equivalent to roughly 8 to 10 t ha^{-1} (Kumar, 2025). The expansion of HDP systems in Kinnaur and adjacent districts creates an urgent need for evidence-based summer pruning protocols calibrated to local agro-climatic conditions.

Physiological Basis of Summer Pruning in Apple

The physiological effects of summer pruning are mediated through three interconnected mechanisms: carbohydrate dynamics and source-to-sink balance, hormonal regulation of flower bud differentiation, and light distribution within the canopy and its consequences for anthocyanin biosynthesis.

Carbohydrate dynamics and source-sink balance:

One of the main purposes of summer pruning is to facilitate light penetration into the bearing area and to maintain an optimum C:N ratio, crucial for apple development (Rehman *et al*., 2021). Li *et al*. (2003a) demonstrated that summer pruning reduces whole-canopy carbon fixation and transpiration in direct proportion to the fraction of foliage removed, but that remaining leaves partially compensate through increased individual photosynthetic rates once shading is relieved. Li *et al*. (2003b) showed that summer pruning effects on fruit size and quality are mediated through the crop load to canopy photosynthesis ratio: when crop load is maintained while leaf area is reduced, per-fruit carbohydrate supply decreases, reducing both fruit size and soluble solids content. This mechanistic understanding explains the observations of Myers and Ferree (1983), who found that midseason July pruning of vigorous Delicious on M.9 decreased fruit size and soluble solids when crop load was not simultaneously adjusted.

Flower bud differentiation: molecular and hormonal mechanisms: The physiological differentiation of apple flower buds occurs from early June to July in the Northern Hemisphere, coinciding with cessation of primary shoot extension. The transition from vegetative to reproductive growth involves genes including MdFT1, MdTFL1, MdBLH14, and multiple microRNAs (miR156, miR172, miR319) that function within conserved floral induction pathways (Xing *et al*., 2016; Qiu *et al*., 2025). Summer pruning operations modify the hormonal environment of bourse buds during this critical window: shoot bending and twisting decrease auxin and gibberellin concentrations, increase cytokinin levels, and promote starch accumulation, all conducive to flower bud induction (Xing *et al*., 2019; Chen *et al*., 2023). Ring wounding interrupts phloem transport, further increasing cytokinin-to-gibberellin ratios at the ring site and in subtending buds (Wang *et al*., 2021; Zhang *et al*., 2023). In summer pruning, water shoots are addressed in two ways: where a large gap exists between two fruit buds, a cut is made just above the ring to activate sleeping buds; while in other shoots a cut of two to three inches is made in water sprouts to convert them into fruit buds in the next year (Rehman *et al*., 2021).

Light dynamics and anthocyanin biosynthesis: Fruit colour development in apple is tightly regulated by light through photoreceptor-mediated activation of the MdMYB10 transcription factor and downstream structural genes of the anthocyanin biosynthetic pathway including chalcone synthase and dihydroflavonol reductase (Chen *et al*., 2021). Jackson (1980) established that fruit quality is directly proportional to the fraction of incident photosynthetically active radiation (PAR) within the canopy, and that light intensities below approximately 35% of external PAR produce inadequately coloured fruit. Summer pruning has been shown to improve light distribution within the canopy and, as a result, increase percent blush on red-blushed cultivars (Porpiglia and Barden, 1981; Autio and Greene, 1990). The coincidence of optimal temperatures for bud differentiation (20 to 27°C) with the elevated radiation levels prevailing in Kinnaur's clear-sky summer creates a uniquely productive window for simultaneous quality improvement and flower bud induction through timely summer pruning (Kumar, 2025; Qiu *et al*., 2025).

Advantages of Summer Pruning

Summer pruning confers a range of agronomic and economic advantages for apple orchardists. The primary aim is to activate sleeping buds, thereby increasing spur numbers per branch and improving return bloom (Rehman *et al*., 2021). It allows sunlight to ripen fruit and ensures good cropping, while also reducing the possibility of secondary vegetative growth (Rehman *et al*., 2021). By providing good aeration and proper sunlight to the apple plant, summer pruning substantially reduces the possibility of fungal disease, helping farmers minimise pesticide use (Rehman *et al*., 2021). The practice stops excessive vegetative growth during the active season and converts vegetative growth into spur formation, which is the primary production objective in apple (Rehman *et al*., 2021). Summer pruning also concentrates fruit maturation, allows for easier harvesting (Rehman *et al*., 2021), and by improving canopy light penetration, re-exposes spur leaves and fruits of the interior canopy (Rom and Ferree, 1984). By reducing the potassium-to-calcium ratio in developing fruit, summer pruning contributes directly to improved calcium nutrition and reduced incidence of bitter pit storage disorder (Guerra and Casquero, 2010; Guerra *et al*., 2021).

Manual Summer Pruning Techniques

When to prune: Summer pruning should be done when the bottom third of the new shoots is stiff and woody, which is the physiological indicator of sufficient basal lignification (Rehman *et al*., 2021). Generally, this condition is reached from mid-July onward in most Himalayan apple orchards. To reduce the possibility of secondary growth, the operation can be delayed until late August in orchards where vigour is high (Rehman *et al*., 2021). This empirical guideline aligns with the physiological readiness criteria of Marini (2024): terminal bud set at the shoot tip, basal lignification producing an audible snap when bent, and the lower one-third of the new season's shoot being hard and woody. Kumar (2025) provides altitude-specific refinements: shoot thinning from June for HDP orchards below 1,500 m, from July for mid-elevation sites at 1,500 to 2,500 m, and from early August for orchards above 2,500 m.

Shoot thinning and heading back: Summer pruning involves two main operations: thinning out, by which water shoots are removed from the base to reduce competition with developing fruit, and heading back, by which a cut is left on some shoots so that fruit buds will appear and vegetative growth is converted to reproductive growth (Rehman *et al*., 2021). New shoots (laterals) longer than 25 cm growing from the main stem should be cut back to three leaves above the basal cluster of leaves, while shoots under 23 cm can generally be left because shorter growth is likely to carry fruit buds naturally (Rehman *et al*., 2021). All upright vigorous growth should be removed completely. If secondary growth occurs after summer pruning, it should be removed in September (Rehman *et al*., 2021). Where a cut is made in shoots, it should always be made on the upper side of the ring, as this ring functions as a physiological speed-breaker that slows the flow of sap, activating sleeping buds below the cut (Rehman *et al*., 2021). In compact HDP spindle trees, competing branches with basal diameter exceeding one-third that of the parent limb should be thinned, retaining approximately 1 cm stub (Maughan *et al*., 2017; Qiu *et al*., 2025).

Branch bending: Physical deflection of upright or semi-upright shoots toward horizontal or sub-horizontal positions suppresses apical dominance and promotes flower bud formation without removal of leaf area. Once a main branch exceeds 30 cm in length, it should be bent as early as possible to maintain a base angle of 90 to 110 degrees from vertical for maximum flower bud induction (Xing *et al*., 2016; Han *et al*., 2008). Kumar (2025) recommends bending scaffold branches of central-leader trees to 45 to 60 degrees from vertical and those of spindle-trained HDP trees on clonal rootstocks to 70 to 90 degrees from vertical. Branch bending is most effective in Fuji-type varieties and least effective in Red Delicious and Jonagold, which have more brittle new shoots (Qiu *et al*., 2025).

Ring wounding, bud-notching, and top pinching: Ring wounding removes a narrow ring of bark 1 to 5 mm wide from a branch or trunk, interrupting phloem transport and creating conditions favouring flower bud induction; wounds should be clean, should not penetrate the xylem, and should heal within approximately 20 days (Zhang, 2011; Qiu *et al*., 2025). Bud-notching (scoring) involves cutting the cambium 1 to 2 mm below target buds without removing bark, promoting formation of short fruit-bearing spurs in varieties with low sprouting rates (Maimaiti *et al*., 2013; Close and Bound, 2017). Top pinching is used on upright branches at 15 to 20 cm and on extended branches at 50 to 60 cm (Qiu and Sang, 2025). Shoot twisting involves rotating semi-woody new shoots 180 degrees at the base, wounding the xylem and phloem without breaking, and is most effective when the shoot has reached 20 cm or more (Qiu *et al*., 2025).

Suitability and Dormant Pruning vs. Summer Pruning

Summer pruning is mainly suitable for apple and pear trees trained as restricted forms including cordon, espalier, fan, pyramid, and spindle bush systems, which are the predominant training forms in modern HDP and UHDP orchards (Rehman *et al*., 2021). Trees grown as traditional standards or bushes are managed primarily with winter dormant pruning.

Dormant pruning is an invigorating process limited to removal of dead, defunct, and diseased branches, performed after harvesting in late winter to avoid winter injury (Rehman *et al*., 2021). Summer pruning, in contrast, is performed in the active season and is specifically intended to reduce excessive vegetative growth and balance vegetative and reproductive growth (Rehman *et al*., 2021; Saure, 1987). Summer pruning has been regarded as less invigorating than dormant pruning because it removes foliage during the active growing season, thereby suppressing the compensatory regrowth that typically follows dormant pruning (Utermark, 1977). Li *et al*. (2003a, 2003b) confirmed that summer pruning reduces whole-canopy carbon fixation in the treatment season without consistently stimulating enhanced shoot extension in the following season. The complementary nature of the two operations means that an integrated programme combining appropriate dormant pruning for tree structure with targeted summer pruning for canopy light management and flower bud induction achieves outcomes not attainable through either operation alone (Wertheim, 2005; Qiu *et al*., 2025).

Effects on Vegetative Growth and Tree Vigour

Myers and Ferree (1983) found that midseason July pruning maintained productivity of vigorous Delicious on M.9, increasing numbers of fruit borne on interior canopy spurs in both experimental years. Autio and Greene (1990) confirmed that summer pruning of McIntosh reduced trunk cross-sectional area increment and suppressed root growth in the treatment season without consistently reducing shoot extension in the following season.

Thakur *et al*. (2025) conducted factorial experiments on peach cv. Early Grande at Neri, Hamirpur, combining three pruning timings with six intensity levels and found that severe summer pruning during the second fortnight of June produced the highest annual shoot growth (35.36 cm), largest leaf surface area (49.02 cm^2), and greatest trunk diameter increment compared to unpruned controls (24.59 cm shoot growth; 37.55 cm^2 leaf area; 8.82% trunk increment). The directional relationships between timing, intensity, and vegetative response are consistent with those reported for apple in HDP systems.

Rehman *et al*. (2024) evaluated varied summer pruning intensities on five predominant apple cultivars including Red Fuji, Jeromine, Red Chief, Redlum Gala, and Super Chief in UHDP orchards at Kulgam, Jammu and Kashmir, and documented a strong negative correlation between pruning severity and crop yield in Red Chief, with medium intensity pruning of approximately 20% canopy removal producing the most favourable balance of productivity and quality across cultivars.

Effects on Flower Bud Formation, Return Bloom, and Crop Yield

Activation of sleeping buds to increase the number of spurs per branch and thereby increase apple production in the coming year is a primary objective of summer pruning (Rehman *et al*., 2021). Heading cuts applied during the critical induction period can compress the conversion of vegetative buds to productive fruit-bearing spurs from two to three years to within a single season (Marini, 2024). Platon and Zagrai (1997) documented that systematic summer pruning reduced the incidence of biennial bearing in apple, a major commercial problem in many traditional Himalayan orchards.

Myers and Ferree (1983) established in their multiyear study that July and August pruning consistently increased numbers of spur-borne fruit in the interior canopy compared to September pruning and unpruned controls. September pruning was associated with reduced spur fruit numbers, attributed to insufficient time following late-season defoliation for accumulation of the photosynthates and hormones needed to complete flower bud development before dormancy onset.

Indian evidence from peach research at YSP UHF Hamirpur is instructive for Himalayan orchardists. Thakur *et al*. (2025) found that pruning during the second fortnight of June advanced flowering phenology by 11 to 15 days compared to unpruned controls, with 25%, 50%, and 75% anthesis achieved on February 1st, 3rd, and 5th respectively in treated trees versus February 12th, 14th, and 20th in controls. Fruit yield was inversely related to pruning severity: lightly pruned trees produced 6.11 kg per tree decreasing to 3.27 kg per tree under the most severe treatment, confirming that excessive summer pruning reduces total fruiting area. Vaibhav (2023) provided the most comprehensive Indian documentation of summer pruning effects specifically in apple HDP systems at Nauni, demonstrating significant improvements in spur quality, return bloom percentage, and production efficiency.

Effects on Fruit Quality

Fruit colour and anthocyanin content: Improvement of fruit colour through restored light penetration is the most consistently documented effect of summer pruning, and this aligns with the practical observation that summer pruning allows sunlight to ripen fruit and ensures good cropping (Rehman *et al*., 2021). Autio and Greene (1990) demonstrated that summer pruning of McIntosh apple improved fruit red colour development. Summer pruning has been shown to improve light distribution within the canopy and, as a result, increase percent blush on red-blushed cultivars (Porpiglia and Barden, 1981; Autio and Greene, 1990). Bhusal *et al*. (2017) confirmed in Korean HDP orchards that summer pruning combined with reflective film significantly improved light distribution and colour in the lower canopy. Musacchi and Serra (2018) concluded that canopy light management through pruning is the single most important controllable driver of red colour in apple. Lugaresi *et al*. (2022) reported that late summer pruning of Fuji significantly increased total phenolic content and antioxidant activity. Kumar (2025) observed that summer pruning in Kinnaur orchards achieves notable colour improvement by exposing interior fruit to the region's characteristically clear, high-radiation summer conditions.

Fruit size, soluble solids, titratable acidity, and phenolics: The effects of summer pruning on fruit size, total soluble solids (TSS), and titratable acidity depend critically on timing and severity relative to physiological crop load. Myers and Ferree (1983) found that July pruning decreased fruit length and diameter and reduced soluble solids when crop load was not simultaneously adjusted. Moderate summer pruning under appropriate timing does not consistently compromise quality. Thakur *et al*. (2025) found that pruning during the second fortnight of June resulted in significantly higher TSS (11.27 vs. 9.46 °Brix in controls) and ascorbic acid content (16.37 vs. 12.08 mg/100 g in controls) in peach. Ashraf *et al*. (2017) reported that summer pruning combined with paclobutrazol significantly improved colour, firmness, and TSS in Red Delicious apple in Jammu and Kashmir.

Calcium nutrition and bitter pit: Bitter pit, a calcium deficiency disorder causing brown corky pits in fruit flesh, is a major source of storage losses in Kinnaur and other high-altitude orchards. Guerra and Casquero

(2010) showed that summer pruning reduced external and internal bitter pit incidence after 180 days of storage by approximately 10%, comparable to the effect of postharvest calcium treatment. Guerra *et al*. (2021) demonstrated that summer pruning reduced the potassium-to-calcium ratio in fruit without negatively affecting weight, colour, TSS, titratable acidity, or sensory quality. Myers and Ferree (1983) specifically documented that July and August pruning reduced cork spot incidence by an average of 60% compared to September pruning and unpruned controls, establishing a compelling practical case for early-season summer pruning in orchards with a history of storage calcium disorders.

Summer Pruning and Disease Management

Canopy microclimate and fungal disease reduction: Summer pruning provides good aeration and proper sunlight to the apple plant, substantially reducing the possibility of fungal disease and helping farmers minimise pesticide use (Rehman *et al*., 2021). Cooley *et al*. (1997) documented that summer pruning in semi-dwarf apple trees decreased hours of relative humidity above 95% within the canopy by 63% and consistently reduced sooty blotch and flyspeck incidence by approximately 50% in unsprayed trees, while also substantially improving fungicide spray penetration. Holb and Kunz (2016) confirmed significant reductions in apple scab severity and powdery mildew incidence in summer-pruned trees in organic production systems. Gonda *et al*. (2006) demonstrated that summer pruning markedly improved solar radiation conditions in apple orchards with directly measurable consequences for fruit quality and microclimate-dependent disease incidence.

Wound infection risks: Summer pruning wounds are vulnerable to infection by Nectria canker (Neonectria ditissima) and fire blight (Erwinia amylovora). Chen *et al*. (2016) demonstrated that temperature, humidity, and wound age significantly affect infection of apple shoot pruning wounds by Valsa mali, establishing that pruning during wet or humid conditions substantially increases wound infection risk. Although summer pruning does not normally cause particular problems for the plant when performed correctly (Rehman *et al*., 2021), in Kinnaur and other Himalayan districts where the monsoon season overlaps with the summer pruning window, pruning should be confined to dry weather periods and tools should be disinfected between trees using 70% ethyl alcohol or locally available distilled fruit spirit to minimise pathogen transfer (Kumar, 2025).

Indian Research Contributions on Summer Pruning

Vaibhav (2023) completed doctoral research at YSP UHF Nauni on effects of summer pruning in apple under HDP, constituting the most comprehensive site-specific Indian study to date and referenced in the global review of Qiu *et al*. (2025). Shree *et al*. (2022), working at the Regional Horticultural Research and Training Station, Mashobra, Shimla, examined pruning effects on growth, yield, and fruit quality of apple cv. Gale Gala on MM.106 rootstock under mid-hill Himachal Pradesh conditions and confirmed significant positive effects of canopy management on fruit colour.

Rehman *et al*. (2021), writing in Indian Farmer journal, provided a widely referenced review synthesising key principles and practical guidelines for summer pruning in Indian apple orchards, establishing an accessible foundation for extension communication with orchardists across Jammu and Kashmir and Himachal Pradesh. Their review highlighted the importance of timing (from mid-July when basal third of shoots is woody), the two-step operation of thinning out and heading back, the role of the ring in activating sleeping buds, and the suitability of restricted training forms for summer pruning management.

Rehman *et al*. (2024) provided evidence from UHDP orchards in Kulgam, Jammu and Kashmir, demonstrating that medium-intensity summer pruning of approximately 20% canopy removal during the first week of August consistently produced the best balance of yield, marketable quality grades, and economic returns across five cultivars tested. Kumar (2025), writing in The Pahadi Agriculture e-Magazine (Volume 3, Issue 7, ISSN 2583-7869, Article ID 10353), synthesised practical guidelines for Kinnaur orchardists identifying three primary objectives of summer pruning: correction and direction of dormant training in young trees, opening of the canopy in bearing orchards, and promotion of spur formation 30 to 40 days before harvest to optimise fruit quality.

Thakur *et al*. (2025), working at YSP UHF Hamirpur and publishing in the Journal of Environmental Biology, established that second-fortnight June pruning consistently outperformed later timings for vegetative growth, flowering advancement, and fruit quality in peach at Neri, Hamirpur (637 m amsl), with severe intensity maximising fruit weight (103.55 vs. 83.71 g control), TSS (12.38 vs. 9.46 °Brix), and ascorbic acid content (19.18 vs. 12.08 mg/100 g), while light intensity produced the highest yield, providing broadly applicable calibration reference points for Himalayan orchardists.

Altitude-Specific Timing Framework for Himalayan Apple Orchards

Synthesising Indian and international evidence, an altitude-specific practical timing framework for summer pruning in Himalayan temperate apple orchards is presented in Table 1. The framework is derived from the altitude-specific guidelines of Kumar (2025), the J&K cultivar trial evidence of Rehman *et al*. (2024), the practical guidelines of Rehman *et al*. (2021), and the physiological criteria established by Myers and Ferree (1983) and Marini (2024).

Table 1: Altitude-specific summer pruning timing framework for Himalayan apple orchards

Tree phase	Elevation / Site	Optimal timing	Principal operations
Young (years 1–5)	Below 1,500 m	June	Shoot thinning; branch bending; lateral spur initiation
Young (years 1–5)	1,500–2,500 m (Kalpa, Nichar blocks)	July	Shoot thinning; branch bending; lateral heading
Young (years 1–5)	Above 2,500 m (Pooh block, upper Sangla)	Early August	Delicate shoot thinning; bending only
Bearing HDP on clonal rootstocks	Mid-elevation sites	From 15 July; complete 30–40 days before harvest	Watersprout removal; canopy opening; spur management; shoot heading
Traditional orchards on vigorous rootstocks	High elevation Kinnaur (above 2,500 m)	Not before 20 August; light only	Delicate pruning only; avoid heavy pruning

(Synthesised from Kumar, 2025; Rehman et al., 2024; Rehman et al., 2021; Myers and Ferree, 1983)

Physiological readiness indicators that should trigger summer pruning, more reliably than calendar dates alone, include: terminal bud set at the shoot tip with no further unfurling of new leaves; basal lignification producing an audible snap when the shoot base is bent; fruit having attained approximately 30 to 55 leaves per fruit for adequate photosynthate supply; and the lower one-third of the new season's shoot being hard and woody (Marini, 2024; Rehman *et al*., 2021; Kumar, 2025).

Practical Challenges and Common Errors

Although summer pruning when correctly performed does not cause particular problems for the plant (Rehman *et al*., 2021), the key to effective practice is performing it in small amounts and over multiple sessions, helping the tree achieve a productive structure with a fruiting branch hierarchy, reasonable spatial distribution, and sunlight exposure for all branches (Qiu *et al*., 2025). In India, most fruit farmers have not undergone systematic pruning training, and assessment of varietal characteristics, tree shape, and tree vigour before intervention is frequently insufficient (Jin *et al*., 2022).

Common errors include untimely branch bending at insufficient angles; twisting too early or too late causing branch damage; excessive thinning or heading back resulting in yield reduction; and leaving long stubs causing excessive regrowth. Kumar (2025) specifically cautions that for traditional orchards on vigorous rootstocks in Kinnaur, summer pruning should not be initiated before 20 August at high elevations. The practical guideline for Kinnaur growers is that only delicate pruning is appropriate in traditional orchards; heavy summer pruning has consistently produced unsatisfactory results at this altitude.

Future Research Priorities

Several important knowledge gaps remain, particularly for Indian Himalayan conditions. The most significant is the near-absence of multi-year, multi-site, replicated trials across the full range of commercial varieties and elevations in the Indian Himalayan apple belt. The work of Rehman *et al*. (2024), Vaibhav (2023), and Shree *et al*. (2022) represents important beginnings but does not cover conditions prevailing in high-altitude orchards above 2,500 m. Research stations at RHRS Mashobra, KVK Kinnaur, and the proposed Centre of Excellence for apple in Himachal Pradesh are well positioned to address this gap through systematic long-term trials.

The carbohydrate models of Li *et al*. (2003a, 2003b) require validation under Indian cultivar and rootstock combinations in Himalayan conditions. The interaction between summer pruning and precision nutrition management, particularly calcium and potassium for bitter pit prevention, is understudied.

Climate change is progressively altering chilling accumulation, flowering phenology, and disease pressure across the Himalayan apple belt, creating a need for research on how summer pruning protocols should adapt as growing conditions evolve. The role of summer pruning in maintaining the optimum C:N ratio under variable seasonal conditions, as emphasised by Rehman *et al*. (2021), merits quantitative investigation under Himalayan agro-climatic parameters.

Conclusion

Summer pruning in apple is the key to good quality fruit production, providing good aeration, reducing fungal infection including Alternaria, and converting vegetative growth into reproductive growth to increase spur numbers and ultimately fruit production (Rehman *et al*., 2021). The practice is most effective when applied after terminal bud set and shoot base woodiness are confirmed, at moderate intensity that maintains adequate leaf area relative to crop load, and completed at least 30 to 40 days before anticipated harvest. Evidence from YSP UHF Nauni, YSP UHF Hamirpur, Mashobra, Kulgam, and KVK Kinnaur, combined with the global synthesis of Qiu *et al*. (2025) and the foundational experimental work of Myers and Ferree (1983) and Autio and Greene (1990), provides a coherent and robust evidence base for the adoption of scientifically calibrated summer pruning across the Indian temperate fruit-growing belt. For the high-altitude, quality-oriented apple production systems of Kinnaur district, summer pruning timed to the unique agro-climatic window created by clear-sky summers, optimal temperatures for bud differentiation, and the expanding base of HDP orchards on clonal rootstocks, represents an investment with exceptional returns in both fruit quality and farmer income.

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