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INFLUENCE OF PLANT GROWTH REGULATORS ON FLOWERING, YIELD AND QUALITY OF SAPOTA (*ACHRAS ZAPOTA* L.): A COMPREHENSIVE REVIEW

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ABSTRACT

Sapota (*Achras zapota* L.), a prominent tropical fruit crop of the family Sapotaceae, ranks among India's most economically significant horticultural species with considerable contribution to national fruit production. Despite its commercial importance, sapota cultivation is severely constrained by irregular bearing, erratic flowering, heavy multi-stage fruit drop, and suboptimal post-harvest quality, collectively reducing farm income substantially below its true potential. Plant growth regulators (PGRs) have emerged as precision agronomic tools capable of overcoming these physiological limitations through targeted hormonal intervention at critical developmental stages. Thee influence of major PGR classes auxins (NAA, 2,4-D), gibberellins (GA_3), cytokinins (BA), ethylene-releasing compounds (ethephon), triazole growth retardants (paclobutrazol), polyamines (spermidine) and brassinosteroids on flowering synchronization, yield improvement, and fruit quality enhancement in sapota. Among all paclobutrazol soil drenching consistently delivered the most superior and comprehensive results across flowering percentage, yield per tree, total soluble solids, vitamin C content, and shelf life extension. Foliar application of NAA significantly advanced first flowering, reduced cumulative fruit drop, and improved overall fruit retention. Ethephon promoted synchronized flowering and enhanced fruit quality through stimulation of the phenylpropanoid biosynthetic pathway. Combined PGR treatments, particularly NAA with BA and paclobutrazol with NAA, outperformed individual applications through synergistic hormonal interactions at the molecular level. Based on the collective weight of evidence, a six-stage integrated PGR management schedule encompassing pre-flowering through pre-harvest interventions is recommended for adoption in commercial sapota orchards. Future research priorities include development of nano encapsulated PGR delivery systems, transcriptomic profiling of PGR-induced floral transitions, bio stimulant integration, and systematic residue safety evaluation to support regulatory framework development.

***Key words*:** Achras zapota, paclobutrazol, NAA, ethephon, gibberellin, fruit set, TSS, irregular bearing, yield, tropical horticulture

Introduction

Sapota [*Achras zapota* L. syn. *Manilkara zapota* (L.) van Royen], known variously as chiku, sapodilla, or naseberry, belongs to the family Sapotaceae and is cultivated across tropical and subtropical Asia, Central America and the Caribbean. India contributes about 70%

of the total production of the species (NHB, 2022), with the main centers of production in Maharashtra, Gujarat, Andhra Pradesh, Karnataka, and Tamil Nadu. It is rich in vitamins and minerals such as vitamin C, vitamin A, dietary fiber, iron, and potassium and is medicinally important in antioxidant, anti-inflammatory, and anti-diarrheal activities (Aravind *et al*., 2014; Gutierrez *et al*., 2016). The latex of the plant is used in the preparation of chewing gum material known as chicle and the wood is prized for its exceptional hardness (Sinha & Jana, 2000). The economic value and distribution of the species along with its ethnobotanical uses have been documented in the publications of Majumder & Hassan (2010) and Goyal & Misra (2009).

Despite the economic importance, the cultivation of commercial sapota is affected by a number of physiological problems. Irregular bearing, also called biennial bearing, where heavy crop years are followed by poor crop years, is one of the most destructive problems in sapota (Singh & Rathore, 2011; Patel & Patel, 1975). The crop history of biennial bearing in India was first documented in the year 1999 by Bankar & Prasad. Erratic flowering in response to temperature and moisture stress makes the prediction of the harvest seasons unpredictable (Singh & Patel, 2009). There is a considerable amount of fruit drop at various stages, viz., 20-45 days after full flowering during active cell division, 60-90 days after full flowering during cell enlargement, and in the pre-harvest stage, leading to a reduction in yield by 40-70% in unmanaged orchards (Rathod *et al*., 2018; Sandhu & Arora, 1992). There is a need to reduce post-harvest losses due to the short shelf life, which adds to the economic burden on the farmers (Patil *et al*., 2011; Kader, 2002). It has been estimated that the realizable income would increase by 60-100% by adopting integrated management practices, including PGRs (Rameshwar & Singh, 2009).

Plant growth regulators (PGRs) are organic substances that at trace concentrations modulate plant growth and development through receptor-mediated signal transduction cascades. The five classical PGR classes auxins, gibberellins, cytokinins, ethylene and abscisic acid are now supplemented by brassinosteroids, polyamines, jasmonates and salicylates as recognized regulatory molecules (Taiz & Zeiger, 2010; Davies, 2010). The biochemical nature and physiological roles of PGRs have been authoritatively reviewed by Gaspar *et al*. (1996) and form the mechanistic framework for agronomic applications. PGR use has successfully resolved biennial bearing in mango (Burondkar *et al*., 2013), improved fruit set in citrus (Agustí *et al*., 2008; El-Otmani *et al*., 2000) and enhanced post-harvest quality in guava (Mishra *et al*., 2018). Auxin effects on fruit thinning in deciduous species an inverse application of PGR fruit-retention science are well documented by Wertheim (1998). Commercial PGR use in fruit cultivation is codified in standard references (ICAR, 2012; Haig & Mito, 2007).

In sapota, PGR research dates to Bhatia & Teaotia (1974), who first tested gibberellic acid on fruit development. Arora & Khanna (1986) subsequently evaluated auxin effects on fruit retention. The field expanded substantially with studies by Chattopadhyay & Bose (1998) on hormonal regulation of tropical fruit development, Singh & Singh (2000) on comparative PGR effects across sapota and related crops, Tripathi & Bhargava (2003) on soil-applied versus foliar PGR regimes and Dharwadkar *et al*., (2009) on growth regulator effects on quality and yield. Detailed cultivar-specific responses were reported by Subramanian & Shanmugavelu (1999) for South Indian varieties. Despite this growing body of evidence, no comprehensive review has synthesized findings across all PGR classes for sapota. The present work addresses this gap, drawing on 78 publications from 1974–2024.

Taxonomy, Distribution and Botanical Description

Systematic Classification:

Achras zapota L. (Kingdom: Plantae; Order: Ericales; Family: Sapotaceae) is currently synonymized as *Manilkara zapota* (L.) van Royen, although the Achras binomial persists in horticultural literature. Vernacular designations include chiku (Hindi, Gujarati, Marathi), sapota (Kannada, Telugu, Tamil), naseberry or sapodilla (English), sapotillier (French) and níspero (Spanish) (Goyal & Misra, 2009). The botanical identity of the species and its synonymy have been discussed in detail by Dhua & Mitra (1991); (Kuteand Shete, M.B., 1995) and Sinha & Jana (2000), both standard references for tropical fruit botany in South Asia.

Morphological Features:

Sapota is an evergreen, slow-growing, long-lived tree that grows 15-20 m in natural conditions, which is pruned to a height of 3-5 m under commercial orchard conditions. Leaves are simple, alternate, elliptic-oblong, in clusters towards the tips of the branches, glossy, dark green on the adaxial surface, etc. Flowers are small, perfect, bell-shaped, axillary, white or creamy white, six sepals in two series, six-lobed corolla, etc. Fruit is round to ovoid, 5-10 cm in diameter, scurfy, russet-brown, berry, 1-12 black, hard seeds, yellowish-brown translucent mesocarp, etc. Milky latex, which exudes from all the plant parts, is a diagnostic feature of Sapotaceae. This feature is also

Table 1: Effect of Different Plant Growth Regulators on Flowering Parameters in Sapota (*Achras zapota* L.) — Compiled from Published Studies (1974–2024).

PGR	Concentration	Days to First Flower	Flowering (% trees)	Reference
NAA	50 ppm	62.4	78.6	Patel & Singh (2010)
NAA	100 ppm	58.2	84.3	
GA_3	50 ppm	71.5	66.2	Sharma *et al*., (2014)
GA_3	100 ppm	74.3	61.8	
2,4-D	10 ppm	60.1	80.4	Kumar & Rao (2012)
2,4-D	20 ppm	56.7	86.1	
Ethephon	200 ppm	55.9	88.5	Reddy *et al*., (2016)
Ethephon	400 ppm	53.1	90.3	Kishore & Bhartiya (1999)
Paclobutrazol	5 g/tree	52.3	91.2	Mishra & Bhatt (2018)
Paclobutrazol	10 g/tree	49.8	94.7	Mishra & Bhatt (2018)
NAA + BA	50+25 ppm	57.4	82.9	Thakur *et al*., (2012)
Control	-	82.6	54.3	-

used to identify the Sapotaceae family (Sinha & Jana, 2000; Chattopadhyay & Bose, 1998). A change in chlorophyll carotenoid complexes, which is a measure of the progress of ripening, was first documented in the context of Indian Sapota by Bhatt & Rao (1987). Fruit morphological characteristics such as length, width, weight, etc., are used as major yield quality parameters in Tables 1 & 3.

Phenology and Cropping Season Management:

In tropical lowlands, sapota may flower and fruit nearly continuously; in subtropical and semi-arid regions, distinct seasons emerge. India recognizes two principal cropping seasons: the *mrig bahar* (June–October flowering; December–April harvest) and the *ambe/hasta bahar* (March–June flowering; August–December harvest). Traditional *bahar* management imposing controlled water stress for 30–45 days followed by resumption of irrigation synchronizes flowering by simulating seasonal drought (Singh & Patel, 2009; Bankar *et al*., 2001). The physiological basis of this practice relates to carbohydrate accumulation under stress, analogous to the mechanism by which paclobutrazol induces regular bearing (Kumar *et al*., 2014). Farmers in Maharashtra and Gujarat have practiced bahar management empirically for generations (Rameshwar & Singh, 2009) and PGR intervention provides a scientific complement to this traditional knowledge.

Plant Growth Regulators: Classes, Chemistry and Mechanism of Action

Auxins:

Auxins are the first class of PGRs discovered, with indole-3-acetic acid (IAA) as the principal endogenous form. Synthetic auxins used commercially include naphthalene acetic acid (NAA), indole-3-butyric acid (IBA), 2,4-dichlorophenoxyacetic acid (2,4-D) and 4-chlorophenoxyacetic acid (4-CPA). Auxin promotes cell elongation via Hz -ATPase-mediated cell wall acidification and is essential for fruit set by maintaining polar auxin transport from developing seeds to the pericarp, thereby suppressing pedicel abscission zone activation (Crane, 1964; Zhao, 2010). At the molecular level, auxin perception involves the SCFTIR1 ubiquitin ligase receptor complex, explaining dose-dependent responses (Zhao, 2010). Auxin effects on fruit development in horticultural species have been reviewed globally by El-Otmani *et al*., (2000) and Ahmad *et al*., (2010) in ber fruit, providing comparative context for sapota research.

In sapota, the earliest evidence of auxin benefit was reported by Arora & Khanna (1986), who documented fruit retention improvements with exogenous hormone application. Later work by Chaudhary *et al*., (2001) characterized the biochemical changes during sapota fruit development linked to endogenous auxin dynamics. Field evaluations by Patel & Singh (2010) established NAA at 100 ppm as a benchmark treatment, reducing days to first flowering from 82.6 to 58.2 days and increasing flowering percentage from 54.3% to 84.3% (Table 1). Fruit drop reduction studies by Rathod *et al*. (2018) confirmed that repeated NAA applications at 30, 60 and 90 DAFS reduced cumulative drop from 68.4% to 38.2%. Cultivar-specific auxin responses were reported by Srinivas *et al*., (2009) and Raju & Reddy (2010) and the early field data from Maharashtra by Sandhu & Arora (1992) confirmed consistent benefits of 50–100 ppm NAA across agroclimatic zones.

Gibberellins:

Gibberellins comprise a large family (>136 known GAs) of diterpenoid carboxylic acids synthesized via the methylerythritol phosphate pathway. GA_3 is the most biologically active and commercially available form. Gibberellins promote stem elongation, seed germination

Table 2: Summary of Major Research Studies on Paclobutrazol Application in Sapota — Dose, Method and Key Outcomes.

Investigator	Dose / Method	% Flowering Trees	Yield Increase (%)	Key Observations
Mishra & Bhatt (2018)	5 g/tree soil drench	91.2	99.4	Improved TSS and fruit size
Mishra & Bhatt (2018)	10 g/tree soil drench	94.7	118.6	Best overall results
Pillai *et al.*, (2020)	7.5 g/tree soil drench	92.8	107.3	Higher chlorophyll content
Verma & Ghosh (2017)	5 g/tree + GA_3	88.4	94.6	Reduced vegetative growth
Nair *et al.*, (2019)	10 g/tree + NAA	96.1	124.8	Highest fruit retention
Chadha & Kumar (2015)	4 g/tree soil	87.6	88.2	Earlier flowering by 3 wks
Yunzhi & Jinhu (2006)	8 g/tree soil	90.4	102.6	Improved C:N ratio in buds
Tripathi & Bhargava (2003)	6 g/tree soil	89.1	96.8	Enhanced shoot:root ratio

and flowering in long-day plants (Yamaguchi, 2008). The biosynthetic pathway particularly the ent-kaurene oxidase step inhibited by triazole growth retardants such as paclobutrazol has been thoroughly characterized (Yamaguchi, 2008). The molecular interaction between GA and DELLA repressor proteins provides the basis for GA-mediated growth responses (Martínez-Fuentes *et al.*, 2010). In sapota, Bhatia & Teaotia (1974) first demonstrated GA_3 effects on fruit development. More recently, Sharma *et al.*, (2014) confirmed that GA_3 at 50 ppm increased panicle length and flower number, but that higher doses (100 ppm) delayed flowering (Table 1). Sonawane *et al.*, (2009) examined GA_3 effects specifically on fruit growth and González *et al.*, (1998) provided comparative data from apple that contextualize the trade-off between GA_3-promoted fruit size and delayed TSS accumulation.

Cytokinins:

Cytokinins including naturally occurring zeatin and commercial 6-benzylaminopurine (BA) and kinetin promote cell division, enhance sink strength, delay senescence and improve nutrient mobilization into fruits (Hussain *et al.*, 2015). Their role in tropical fruit crops has been comprehensively reviewed by Akhter *et al.*, (2015). In sapota, BA at 25–50 ppm applied at full bloom improves fruit set by stimulating endosperm and pericarp cell division (Maheshwari *et al.*, 2015). Combined NAA + BA application, studied by Thakur *et al.*, (2012) and Joshi & Verma (2019), produced synergistic improvements in fruit weight and TSS beyond what either treatment achieved alone (Table 1). The stay-green effect of BA, extending functional leaf and fruit life, has practical implications for post-harvest quality maintenance (Hussain *et al.*, 2015). Cytokinin signal transduction through two-component His-Asp phosphorelay systems is well characterized (Gaspar *et al.*, 1996), providing a mechanistic framework for these observations.

Ethylene and Ethylene-releasing Compounds:

Ethylene is the gaseous plant hormone governing fruit ripening, senescence and abscission. Ethephon (2-chloroethylphosphonic acid) releases ethylene upon contact with plant tissue at pH > 4.0 and is the principal commercial ethylene-releasing compound. The biochemistry of ethylene in tropical fruit ripening has been comprehensively reviewed by Vazques-Collazo & Martínez-Téllez (2010). In sapota, pre-harvest ethephon at 200–400 ppm promotes earlier, more uniform flowering and fruit ripening (Reddy *et al.*, 2016; Kishore & Bhartiya, 1999). Ethephon also reduces the gritty texture of stone cells and improves skin colour (Sandip *et al.*, 2015; Chandramohan *et al.*, 2009). Pre-harvest salicylic acid + ethephon interaction on post-harvest quality was specifically investigated in sapota by Kishore *et al.*, (2008), adding nuance to simple ethephon recommendations. The molecular pathway upregulation of ACC synthase and ACC oxidase underpins the fruit-ripening response (Vazques-Collazo & Martínez-Téllez, 2010).

Growth Retardants: Paclobutrazol:

Paclobutrazol (PBZ), a triazole-class growth retardant, inhibits the ent-kaurene oxidase step of the GA biosynthesis pathway, reducing endogenous GA levels, suppressing vegetative shoot growth and redirecting photosynthate to reproductive organs (Yunzhi & Jinhu (2006)). Indirect effects include enhanced chlorophyll content, improved carbohydrate accumulation in buds, elevated C:N ratio and increased antioxidant enzyme activity (Mishra & Bhatt, 2018; Pillai *et al.*, 2020). PBZ soil drenching at 5–10 g a.i./tree produced the most consistently superior results among all PGR interventions tested in sapota (Tables 1, 2, 3, 4). Chadha & Kumar (2015) demonstrated earlier flowering by three weeks with PBZ at 4 g/tree. Verma & Ghosh (2017) showed that combining PBZ with GA_3 modulated vegetative suppression while retaining floral benefits. Nair *et al.*, (2019) achieved the highest reported fruit retention index (96.1% flowering trees) when PBZ at 10 g/tree was combined with NAA. Tripathi & Bhargava (2003) established the comparative superiority of soil-applied

Table 3: Effect of Plant Growth Regulators on Fruit Quality Parameters of Sapota (*Achras zapota* L.).

Treatment	Conc. / Dose	TSS (°Brix)	Acidity (%)	Total sugar (%)	Reducing Sugar (%)	Vit. C (mg/ 100 g)	Tannin (%)	Shelf Life (days)	Reference
Control	-	20.4	0.18	12.6	8.4	14.8	0.24	8.2	—
NAA	50 ppm	23.1	0.16	14.8	9.6	17.2	0.19	10.4	Patel & Singh (2010)
NAA	100 ppm	24.6	0.14	15.9	10.4	18.6	0.17	11.8	Rathod *et al*., (2018)
GA_3	50 ppm	21.8	0.17	13.9	9.1	15.9	0.22	9.3	Sharma *et al*., (2014)
GA_3	100 ppm	22.4	0.16	14.4	9.4	16.4	0.21	9.8	Sharma *et al*., (2014)
2,4-D	10 ppm	23.8	0.15	15.3	9.9	17.8	0.18	11.1	Kumar & Rao (2012)
CPPU	5ppm	16.85	084	9.51	-	-	-	-	Naik *et al*., 2022
Ethephon	200 ppm	25.2	0.13	16.4	10.8	19.1	0.16	12.6	Reddy *et al*., (2016)
Ethephon	400 ppm	25.8	0.12	16.9	11.1	19.6	0.15	13.1	Kishore & Bhartiya (1999)
Paclobutrazol	5 g/tree	26.1	0.12	17.2	11.4	20.4	0.14	13.4	Mishra & Bhatt (2018)
Paclobutrazol	10 g/tree	27.3	0.11	18.1	12.2	21.6	0.13	14.2	Mishra & Bhatt (2018)
NAA + BA	50 + 25 ppm	24.9	0.14	16.1	10.6	18.9	0.17	11.6	Thakur *et al*., (2012)
Spermidine	1.0 mM	22.9	0.16	14.6	9.7	17.4	0.20	12.8	Mukherjee & Chattopadhyay (2019)
Salicylic Acid	100 ppm	23.4	0.15	15.1	9.8	18.2	0.18	13.6	Kishore *et al*., (2008)
1-MCP	1.0 µL/L	22.1	0.17	13.8	8.9	15.6	0.23	16.4	Sharma & Dhaliwal (2021)
Epibrassinolide	0.5 ppm	22.6	0.16	14.2	9.3	16.8	0.21	10.8	Kaur & Singh (2021)

TSS = Total Soluble Solids | Vit C = Vitamin C (Ascorbic Acid) |

over foliar PBZ in sapota, confirmed later by Pillai *et al*., (2020). The historical context of PBZ as an off-season flowering management tool in tropical trees was established in subtropical species by Yunzhi & Jinhu (2006) and linked to general growth-retardant literature by Grochowska *et al*., (1983).

Polyamines:

Polyamines putrescine, spermidine and spermine are low-molecular-weight polycationic compounds with regulatory roles in cell division, fruit development and stress tolerance. They compete with ACC for SAM (S-adenosylmethionine), thereby inhibiting ethylene biosynthesis at critical developmental stages (Mukherjee & Chattopadhyay, 2019). Mukherjee & Chattopadhyay (2019) demonstrated that spermidine at 0.5–1.0 mM significantly extended sapota shelf life from 8.2 to 12.8 days and reduced pre-harvest fruit drop, positioning polyamines as promising alternatives to synthetic PGRs. Polyamine-mediated shelf-life extension is particularly valuable in the context of sapota's short post-harvest window (Northcutt & Phipps, 2006).

Brassinosteroids and Salicylates:

Brassinosteroids (BRs) are steroidal PGRs involved in cell elongation, pollen tube growth, stress signaling and photosynthetic enhancement. Epibrassinolide at 0.1–1.0 ppm has been investigated in sapota for improving fruit set and reducing heat-stress damage (Kaur & Singh, 2021). Salicylic acid (SA) at 100–200 ppm acts as a signal molecule enhancing antioxidant capacity, improving photosynthetic rate and reducing post-harvest disease incidence (Kaur & Singh, 2021; Kishore *et al*., 2008). The role of these PGR classes in regulating plant responses to environmental stresses relevant to fruit development has been reviewed in a general plant physiology context by Lerner (1999). Although studies specifically on BRs and SA in sapota remain limited, the foundational data from Kaur & Singh (2021) are promising and justify expanded investigation.

CPPU:

CPPU (Forchlorfenuron) is a highly effective, synthetic cytokinin-based plant growth regulator (PGR) used in sapota (*Achras zapota* L.) to enhance fruit size, weight, and quality. It stimulates rapid cell division and expansion, leading to better fruit retention and increased pulp weight.

Effect of PGRs on Flowering in Sapota

Induction and Synchronization of Flowering:

Irregular and asynchronous flowering is the major limiting factor in the commercial cultivation of sapota. The need for synchronized flowering is a pre-condition for the development of the fruit, efficient harvesting, and market supply. The conventional method of bahar

Table 4: Molecular and Biochemical Mechanisms of Plant Growth Regulator (PGR) Action in Sapota (*Achras zapota* L.).

Compiled from Published Studies (1964–2024) | ↑ = Increase ↓ = Decrease TF = Transcription Factor SuSy = Sucrose Synthase CWI = Cell-wall Invertase

PGR / Compound	Receptor / Perception	Key Enzymes & Proteins	Biochemical Effect	Agronomic Outcome in Sapota	Reference
NAA (Auxin)	TIR1 F-box receptor (nuclear)	ACC synthase, H^+ -ATPase, SuSy, CWI	Cell elongation, abscission suppression, ↑ sugar import	Days to flower 82.6→58.2; Fruit drop 68.4→38.2%; TSS ↑ to 24.6 °Brix	Patel & Singh (2010); Rathod *et al*., (2018)
2,4-D (Auxin)	TIR1/AFB F-box (nuclear SCFTIR1)	Phospholipase D, Peroxidase, PCNA	Parthenocarpy; ↑ pericarp cell division; pedicel abscission blocked	Fruit set ↑ 85%; Yield 10.53 kg/tree vs 7.14 kg control	Kumar & Rao (2012)
GA_3 (Gibberellin)	GID1 soluble nuclear receptor	GA20-ox, GA3-ox, DELLA repressors, α-Amylase	DELLA degradation → stem/fruit elongation; ↑ flower number at 50 ppm	Panicle length ↑; Fruit wt ↑ 11.4%; TSS 22.4 °Brix (lower than PBZ)	Sharma et al. (2014); Yamaguchi (2008)
BA (Cytokinin)	AHK2/AHK3/ AHK4 His-kinase (membrane)	CDKs, D-type Cyclins, SuSy, CKX	↑ Cell division; ↑ pollen germination; delays senescence; ↑ sink strength	Pollen germination 62.4→82.7%; Fruit set ↑ 34.2%; Fruit wt 117.4 g	Thakur et al. (2012); Maheshwari *et al*., (2015)
Ethephon (Ethylene)	ETR1/ETR2 Cu^{2+} ER-membrane receptors	ACS, ACO, PG, PME, Cellulase, PAL, CHS	Ripening gene expression; cell wall softening; ↑ phenylpropanoids	Flowering 88.5%; Yield 12.69 kg/tree; TSS 25.2 °Brix; Shelf life 12.6 d	Reddy *et al*., (2016); Vazques-Collazo & Martínez-Téllez (2010)
1-MCP (ETH blocker)	ETR1 receptor (irreversible binding)	PG, PME, Cellulase (all inhibited), ACO	Ripening cascade blocked; firmness retained; ↓ chlorophyll loss	Shelf life 16.4 d (longest); TSS 22.1 °Brix; Tannin 0.23%	Sharma & Dhaliwal (2021)
Paclobutrazol	ent-kaurene oxidase (CYP88A, plastid)	KO, DELLA (elevated), SOD, CAT, POD, Rubisco	↓ GA → vegetative suppression; ↑ C:N ratio; ↑ photosynthesis; ↑ ABA	Flowering 94.7%; Yield 15.61 kg/tree (+118.6%); TSS 27.3 °Brix; Shelf life 14.2 d	Mishra & Bhatt (2018); Yunzhi & Jinhu (2006)
Spermidine (Polyamine)	SAM (substrate competition — no dedicated receptor)	SAMDC, SPDS, DAO, PAO, TGase	↓ ACC → ↓ ethylene; ↑ membrane integrity; ↑ SOD/CAT; ↓ PG activity	Shelf life 8.2→12.8 d (+56%); Fruit drop ↓; Vit C maintained; MDA ↓ 28%	Mukherjee & Chattopadhyay (2019)
Epibrassinolide (BR)	BRI1 LRR-RK plasma membrane receptor	BIN2 kinase, BZR1/BES1 TFs, Rubisco activase, SOD	↑ Cell elongation + division; ↑ antioxidant defense under heat stress	Fruit set ↑ under heat stress; Chlorophyll ↑ 12–18%; SOD ↑ 22%	Kaur & Singh (2021)
Salicylic Acid	NPR1 / NPR3/NPR4 (cytoplasmic)	PAL, CHS, APX, GPX, CAT, ICS, PR proteins	↑ Phenolics & flavonoids; ↑ antioxidant capacity; ↑ cell wall lignin	Phenolics ↑ 28.4%; Shelf life ↑ 18%; Post-harvest disease ↓	Kishore et al. (2008); Kaur & Singh (2021)

Abbreviations: ACS = ACC synthase; ACO = ACC oxidase; APX = Ascorbate peroxidase; BA = 6-Benzylaminopurine; BRI1 = Brassinosteroid Insensitive 1; CAT = Catalase; CDK = Cyclin-dependent kinase; CHS = Chalcone synthase; CKX = Cytokinin oxidase; CWI = Cell-wall invertase; DAO = Diamine oxidase; DELLA = Asp-Glu-Leu-Leu-Ala repressor; GA = Gibberellin; GID1 = GA receptor; GPX = Glutathione peroxidase; ICS = Isochorismate synthase; IPT = Isopentenyl transferase; KO = ent-Kaurene oxidase; LRR-RK = Leucine-rich repeat receptor kinase; MDA = Malondialdehyde; NPR1 = Non-expressor of PR genes 1; PAL = Phenylalanine ammonia lyase; PAO = Polyamine oxidase; PCNA = Proliferating cell nuclear antigen; PG = Polygalacturonase; PME = Pectinmethylesterase; POD = Peroxidase; PR = Pathogenesis-related proteins; SAM = S-adenosylmethionine; SAMDC = SAM decarboxylase; SOD = Superoxide dismutase; SPDS = Spermidine synthase; SuSy = Sucrose synthase; TGase = Transglutaminase; TIR1 = Transport Inhibitor Response 1; TSS = Total soluble solids.

management, which induces stress, depends upon physiological rest, which is either drought or temperature-related, but its occurrence cannot be predicted (Singh & Patel, 2009). The application of PGRs, specifically growth retardants, and ethylene release agents offers a reliable method of synchronizing flowering (Kumar *et al*., 2014).

Paclobutrazol at 5–10 g a.i./tree applied as a soil drench 3–4 months before expected flowering has delivered the most consistent synchronization results. Mishra & Bhatt (2018) reported a 74.4% increase in the percentage of flowering trees with PBZ at 10 g/tree, with flowering advanced by 3–4 weeks. Chadha & Kumar (2015) confirmed three-week advancement with the lower dose of 4 g/tree. Tripathi & Bhargava (2003) showed that PBZ at 6 g/tree increased flowering to 89.1% of trees and Yunzhi & Jinhu (2006) documented an improved C: N ratio in terminal buds as the physiological driver of PBZ-induced floral transition. The elevated carbohydrate reserves under PBZ upregulate Flowering Locust (FT) homolog expression and suppress vegetative meristem identity genes (Mishra & Bhatt, 2018)

Ethephon at 200–400 ppm, applied at the pre-dormancy stage, also induced effective flowering synchronization. Reddy *et al*., (2016) found that two sprays of ethephon at 200 ppm at 60-day intervals increased flowering shoot percentage from 54.3% to 88.5% (Table 1). Kishore & Bhartiya (1999) reported that 400 ppm ethephon gave 90.3% flowering trees comparable to PBZ at the lower dose. Ethephon-released ethylene activates phenylalanine ammonia lyase (PAL) and other phenylpropanoid enzymes involved in floral signal transduction (Chandramohan *et al*., 2009). The interaction between ethephon and drought stress was examined by Reddy *et al*., (2016), confirming a 22.4% greater flowering response when ethephon was applied at the break-of-drought irrigation.

NAA at 50–100 ppm, applied at flush emergence, reduced days to first flower opening by 15–24 days versus control. Patel & Singh (2010) established NAA at 100 ppm as the benchmark auxin treatment (Table 1). Dharwadkar *et al*., (2009) independently confirmed earlier flowering with NAA in the Konkan region of Maharashtra. Bankar &

Table 5: Comparative Efficacy of Major PGR Classes for Key Horticultural Traits in Sapota — Summary Based on Weight of Evidence (78 Studies, 1974–2024).

PGR Class	Best for Flowering	Best for Yield	Best for Quality	Recommended Rate
Auxins (NAA/2,4-D)	Moderate (++)	Good (+++)	Good (+++)	NAA 100 ppm foliar
Gibberellins (GA_3)	Low (+)	Moderate (++)	Moderate (++)	50–100 ppm foliar
Cytokinins (BA)	Moderate (++)	Moderate (++)	Good (+++)	50 ppm foliar
Ethylene (Ethephon)	High (++++)	Very Good (++++)	Very Good (++++)	200–400 ppm spray
Triazoles (PBZ)	Excellent (+++++)	Excellent (+++++)	Excellent (+++++)	5–10 g/tree soil drench
Polyamines	Low–Moderate	Moderate (++)	Good (+++)	0.5–1.0 mM spray
Brassinosteroids	Low–Moderate	Moderate (++)	Good (+++)	0.1–1.0 ppm spray

Prasad (1999) contextualized these findings within the biennial bearing literature, proposing that auxin-improved fruit retention in a bearing year reduces the carbohydrate debt that causes a subsequent non-bearing year.

Flower Morphology, Pollen Quality and Fruit Set:

A significant proportion of sapota flowers abort before or shortly after anthesis due to pollen non-viability, insufficient stigma receptivity, or failure of pollination in hot, dry conditions. Maheshwari *et al.*, (2015) demonstrated that BA at 50 ppm increased pollen germination from 62.4% to 82.7% and improved the stigma receptivity index by 34.2%. NAA-mediated auxin maintenance in the ovary sustained fertilization conditions and promoted early fruit development. Singh & Patel (2009) documented that floral drop within 7–10 days of anthesis was linked to auxin deficiency in the pistil and could be corrected by exogenous NAA application.

Fruit set — the proportion of opened flowers that form persistent fruitlets — is the critical determinant of harvestable yield. Kumar & Rao (2012) showed 2,4-D at 20 ppm increased fruit set from 22.6% to 41.8% (85.0% improvement). NAA at 100 ppm gave a 72.1% improvement in fruit set and GA3 at 50 ppm a 28.4% improvement. Subramanian & Shanmugavelu (1999) confirmed differential cultivar responses to PGR-based fruit set improvement, highlighting the need for cultivar-specific recommendations. Thakur *et al.*, (2012) showed that the NAA + BA combination gave the highest fruit set of any treatment tested (Table 1 data; Table 2 follow-through in yield).

Effect of PGRs On Yield and Yield Components

Fruit Retention and Drop Reduction:

Post-fruit-set drop is multi-staged in sapota: cell division stage (20–45 DAFS), cell enlargement stage (60–90 DAFS) and pre-harvest stage (2–4 weeks before maturity). Cumulative drop may exceed 60–70% in unmanaged orchards (Rathod *et al.*, 2018). Rathod *et al.*, (2018) demonstrated that three NAA sprays at 30, 60 and 90 DAFS reduced drop from 68.4% to 38.2% by maintaining an auxin:ethylene ratio above the critical abscission threshold at each stage. Joshi & Verma (2019) showed that NAA (50 ppm) + BA (25 ppm) combined spray at 45 DAFS reduced drop from 64.3% to 31.7%, attributing this to synergistic abscission suppression and cytokinin-promoted fruit cell viability. Earlier work by Bankar & Prasad (1999) had established the commercial significance of drop management for biennial bearing mitigation and Dharwadkar *et al.*, (2009) quantified drop reduction under diverse PGR regimes in commercial orchards.

Fruit Size, Weight and Dimensions:

Fruit size is determined by the number of cell divisions in the pericarp (0–45 DAFS) multiplied by average cell volume (45–120 DAFS). GA_3 and cytokinins act primarily at the cell division phase; auxins and PBZ improve fruit size through improved photosynthate partitioning and sustained cell expansion. Sharma *et al.*, (2014) documented a 11.4% increase in fruit weight with GA3 at 100 ppm. Patel & Singh (2010) showed a 20.4% increase with NAA at 100 ppm. Kumar & Rao (2012) reported a 16.5% improvement with 2,4-D at 10 ppm and Sonawane *et al.*, (2009) confirmed that GA_3 promoted cell elongation but at the cost of delayed TSS accumulation — a trade-off that requires careful dose management. Mishra & Bhatt (2018) documented a 33.1% improvement in fruit weight with PBZ at 10 g/tree, the highest recorded in the literature.

Yield per Tree:

Table 2 presents comprehensive yield data from various PGR treatments compiled from field experiments conducted across sapota-growing regions of India. Among treatments evaluated, PBZ at 10 g/tree gave the highest yield of 15.61 kg/tree versus 7.14 kg/tree in control (118.6% increase). PBZ at 5 g/tree gave 14.24 kg/tree (99.4% increase). Ethephon at 200 ppm delivered 12.69 kg/tree (77.7% increase). NAA at 100 ppm yielded 11.46 kg/tree (60.5% increase). The NAA + BA combination gave 11.49 kg/tree (60.9% increase). Srinivas *et al.*,

(2009) confirmed consistent yield gains with NAA in the DHS-1 cultivar. Raju & Reddy (2010) extended these findings to the Kirthibarthi variety, providing cultivar-level validation. Bankar *et al*., (2001) demonstrated that fruit set improvement through PGR application directly translated to reduced biennial bearing amplitude, with bearing regularity improving from every other year to annual cropping in PBZ-treated trees in a three-year field study.

Detailed Analysis of Paclobutrazol Studies:

Table 4 presents data from major paclobutrazol studies in sapota. The method of application significantly influences PBZ efficacy: soil drenching consistently outperforms foliar spraying, as established by Pillai *et al*. (2020) (soil drench at 7.5 g a.i./tree gave results comparable to the 10 g foliar rate). Nair *et al*., (2019) achieved the highest recorded flowering percentage (96.1%) by combining PBZ at 10 g/tree with NAA, demonstrating synergistic complementation — PBZ induces floral initiation while NAA promotes set retention. Verma & Ghosh (2017) showed that co-application of GA3 can moderate excessive vegetative suppression from PBZ, creating a balanced treatment suitable for young trees. Yunzhi & Jinhu (2006) provided comparative data from subtropical China, confirming that PBZ benefits are not India-specific but apply across diverse environments.

Effect of PGRs on Fruit Quality Parameters

Total Soluble Solids (TSS) and Sugar Profile:

TSS (°Brix) reflects the combined concentration of sugars, acids, amino acids and solutes in fruit juice and is the primary commercial eating-quality index for sapota. The primary sugars — sucrose, fructose and glucose — are regulated by sucrose synthase (SuSy) and cell-wall invertase (CWI). Mishra & Bhatt (2018) reported TSS of 27.3 °Brix with PBZ at 10 g/tree versus 20.4 °Brix in control (33.8% improvement). The mechanism involves PBZ-enhanced phloem sucrose loading, increased SuSy activity and improved photosynthate partitioning (Yunzhi & Jinhu (2006)). Ethephon at 200 ppm gave TSS of 25.2 °Brix (Reddy *et al*., 2016; Sandip *et al*., 2015). GA3 treatments gave more modest TSS increases (21.8–22.4 °Brix) (Sharma *et al*., 2014) and González *et al*., (1998) explain the GA_3-TSS trade-off in terms of delayed invertase activation. Chaudhary *et al*., (2001); Siddiqui *et al*., (2014) and Subramanian & Shanmugavelu (1999) provided early cultivar-specific TSS data that established the baseline for comparative studies (Table 3).

Acidity, TSS: Acid Ratio and Palatability:

Total titratable acidity (TTA) in sapota is generally low (0.10–0.25% as citric acid equivalents) and the TSS: acid ratio is a key palatability index. All PGR treatments in Table 3 reduced acidity relative to control (0.18%). PBZ at 10 g/tree gave the lowest acidity (0.11%), followed by ethephon at 200 ppm (0.13%). The reduction in acidity with auxin treatments is attributed to increased activity of malic enzyme and fumarase, channelling organic acids into energy metabolism rather than fruit accumulation (Rathod *et al*., 2018). Tripathi & Bhargava (2003) confirmed that soil-applied PBZ significantly improved the TSS: acid ratio compared to foliar treatments across three sapota cultivars.

Vitamin C and Phenolic Content:

Vitamin C (ascorbic acid) is both a nutritional quality marker and a post-harvest stability index in sapota. Its biosynthesis from glucose-6-phosphate via the Smirnoff-Wheeler pathway in the chloroplast is enhanced under high photosynthetic activity (Taiz & Zeiger, 2010). PBZ at 10 g/tree increased vitamin C from 14.8 to 21.6 mg/100 g (45.9% improvement) (Table 3). Pillai *et al*., (2020) attributed this to higher chlorophyll content and photosynthetic rate in PBZ-treated trees. Ethephon at 200 ppm gave 19.1 mg/100 g. Total phenolic content — relevant to antioxidant capacity — was quantified by Kishore *et al*., (2008) in salicylic acid + ethephon-treated sapota, showing 28.4% higher total phenolics than control. Sandip *et al*. (2015) similarly reported enhanced phenolic accumulation with ethephon treatment, consistent with ethylene-induced activation of the phenylpropanoid pathway.

Tannin Content and Astringency Reduction:

Sapota fruit contains condensed tannins (proanthocyanidins) responsible for astringency in unripe or prematurely harvested fruits. PGR treatments that accelerate synchronized ripening notably ethephon and PBZ reduce perceived astringency by promoting tannin polymerization and cellular compartmentalization. PBZ at 10 g/tree reduced tannin from 0.24% to 0.13% (Table 3); ethephon at 200 ppm reduced it to 0.16%. Early tannin characterization in sapota during ripening was provided by Bhatt & Rao (1987), establishing the developmental baseline. Chandramohan *et al*., (2009) demonstrated ethephon-mediated tannin reduction and its relationship to improved consumer acceptability (Table 3). Subramanian & Shanmugavelu (1999) provided cultivar-level tannin data showing substantial genotypic variation that influences PGR response magnitude.

Post-Harvest Quality and Shelf Life Extension:

Shelf life extension is a primary commercial objective in sapota marketing. Untreated fruit has 3–5 days ambient

shelf life; PGR-mediated improvements reduce post-harvest losses significantly (Patil *et al*., 2011; Kader, 2002). PBZ at 10 g/tree extended shelf life to 14.2 days (73.2% increase) (Table 3), attributed to enhanced cell wall integrity, reduced ethylene production in harvested fruit, lower polygalacturonase activity and improved cuticle thickness (Nair *et al*., 2019). Spermidine at 1.0 mM extended shelf life to 12.8 days by competing with ACC for SAM, reducing ethylene biosynthesis in harvested fruit (Mukherjee & Chattopadhyay, 2019). Post-harvest 1-MCP fumigation (ethylene receptor blocker) at 1.0 µL/L extended shelf life to 16.4 days (Table 3) while maintaining acceptable TSS (Sharma & Dhaliwal, 2021). Post-harvest packaging and storage physiology for sapota in the broader context of tropical fruit postharvest technology were authoritatively reviewed by Northcutt & Phipps (2006).

Interaction Effects and Combined PGR Treatments

Auxin × Cytokinin Synergy:

The classical auxin:cytokinin ratio governs the balance between root and shoot organogenesis in vitro (Gaspar *et al*., 1996) and analogous interactions regulate fruit development in vivo. Combined NAA + BA application at sub-optimal individual doses showed synergistic effects in sapota, with Joshi & Verma (2019) reporting a 28.4% yield advantage over either treatment alone. Thakur *et al*., (2012) independently confirmed synergistic improvement in fruit weight (117.4 g vs. 112.4 g for NAA alone and 98.6 g control) and TSS. The physiological basis is auxin-suppressed abscission complemented by cytokinin-promoted pericarp cell division, effectively extending the developmental window for fruit growth. Maheshwari *et al*., (2015) further demonstrated that BA improved pollen viability and stigma receptivity, providing an additional advantage in fruit set when combined with NAA.

Paclobutrazol × Nutrition Interactions:

PBZ efficacy is substantially influenced by tree nitrogen status. Chadha & Kumar (2015) showed that PBZ at 5 g/tree in trees receiving optimum nitrogen (500 g N/tree/year) outperformed PBZ in over-fertilized trees (750 g N/tree/year) by 18.6% in yield, as excess nitrogen stimulated the very vegetative growth PBZ was designed to suppress. Akhter *et al*., (2015) provided a theoretical framework for understanding nutrient × PGR interactions in tropical tree crops, emphasizing that balanced NPK fertilization is a prerequisite for optimal PGR response — a principle applicable across all PGR classes reviewed here. Interactions between PBZ and potassium, which modulates sucrose transport, were highlighted by Singh & Singh (2000) as a promising but understudied area.

Ethephon × Irrigation Interactions:

Ethephon effectiveness is amplified when applied after a brief drought-stress period, as stress-primed trees show enhanced ethylene sensitivity. Reddy *et al*., (2016) demonstrated a 22.4% greater flowering response when ethephon at 200 ppm was applied at the break-of-drought irrigation compared to application under normal irrigation scheduling, directly linking traditional bahar management with the PGR rationale. Singh & Patel (2009) mechanistically explained this interaction: drought-accumulated proline and ABA prime the ethylene signal cascade, amplifying the response to exogenous ethephon. Rameshwar & Singh (2009) documented farmer-level outcomes in Maharashtra where integrating irrigation timing with ethephon application improved yield regularity across five-year periods compared to either practice alone.

GA_3 × Auxin Antagonism:

High-dose GA_3 can antagonize auxin-mediated fruit retention by promoting vegetative shoot elongation that competes for photosynthate and by partially reversing auxin-induced changes in abscission zone sensitivity. Sharma *et al*., (2014) observed that GA_3 at 100 ppm reduced the benefit of concurrent NAA application by approximately 14% compared to NAA alone. González *et al*., (1998) and Martínez-Fuentes *et al*., (2010) provide comparative evidence from other tree fruits confirming this interaction. This antagonism supports the recommendation to use GA_3 primarily for fruit enlargement at 50 ppm in the absence of high auxin concentrations, rather than as a universal flowering promotant.

Molecular and Biochemical Mechanisms of PGR Action

Signal Transduction Pathways:

Auxin perception through the SCFTIR1 ubiquitin ligase complex leads to AUX/IAA repressor degradation and ARF transcription factor activation (Zhao, 2010). Gibberellins are perceived by GID1 receptors, triggering DELLA protein degradation and de-repression of GA-responsive genes (Yamaguchi, 2008). Cytokinin signaling operates through two-component His-Asp phosphorelay systems (Gaspar *et al*., 1996). Ethylene is perceived by ETR1/EIN4 receptors; ethylene binding inactivates CTR1, releasing the EIN2/EIN3 cascade for transcriptional activation of ripening genes (Vazques-Collazo & Martínez-Téllez, 2010). PBZ acts upstream in the terpenoid pathway, reducing GA levels and

consequently elevating ABA, which promotes carbohydrate allocation to reproductive organs and triggers floral gene expression (Yunzhi & Jinhu, 2006). These pathways interact extensively: auxin promotes ethylene biosynthesis at ripening while suppressing it at the abscission zone, explaining the complex dose × timing requirements for optimal PGR management (Taiz & Zeiger, 2010)

Key Enzymatic Targets:

Sucrose synthase (SuSy) and cell-wall invertase (CWI) govern sugar import into fruits and are positively regulated by auxin and cytokinin (Hussain *et al*., 2015). Polygalacturonase (PG), pectinmethylesterase (PME) and cellulase govern cell wall dissolution during ripening and are ethylene-induced (Vazques-Collazo & Martínez-Téllez, 2010). ACC synthase (ACS) and ACC oxidase (ACO) are the rate-limiting enzymes of ethylene biosynthesis, upregulated by ethephon and downregulated by polyamine competition for SAM (Mukherjee & Chattopadhyay, 2019). Antioxidant enzymes — superoxide dismutase (SOD), peroxidase (POD), catalase (CAT) — are enhanced by PBZ treatment, reducing oxidative damage during reproductive development (Mishra & Bhatt, 2018). Phenylalanine ammonia lyase (PAL) — the entry enzyme of the phenylpropanoid pathway — is activated by ethylene and SA, explaining the phenolic and antioxidant enhancements observed with ethephon and salicylate treatments (Kishore *et al*., 2008)

Hormonal Crosstalk During Fruit Development:

Fruit development in sapota involves sequential hormonal dominance: high auxin + low ethylene during fruit set and early development; rising gibberellin during cell division; peak cytokinin during endosperm development; declining auxin + rising ABA during maturation; and ethylene surge at ripening (Chattopadhyay & Bose, 1998; Taiz & Zeiger, 2010). Exogenous PGR applications that amplify or supplement natural hormonal transitions at the appropriate timing produce the greatest agronomic responses. Babu *et al*., (2011) compared hormonal dynamics across multiple tropical fruit species including sapota, confirming the general validity of this sequential crosstalk model. Williamson & Coston (1990) provide comparative data on hormonal sink-source interactions relevant to interpreting PGR effects on photosynthate partitioning into sapota fruits. Yadav *et al*., (2012) reviewed gibberellin effects on vegetable crops that, by contrast, illustrate the tissue-specificity of GA responses and the importance of developmental stage in determining GA_3 efficacy in sapota.

Comparative Efficacy and Practical Recommendations

Overall PGR Performance Summary:

Table 5 presents a comparative efficacy summary of PGR classes for flowering, yield and quality improvement in sapota, based on the weight of evidence from all 78 reviewed publications.

Recommended Integrated PGR Management Schedule:

Based on the reviewed literature, the following six-stage integrated schedule is recommended for commercial sapota orchards in India:

Stage 1 Pre-flowering (3–4 months before expected bloom): Paclobutrazol soil drench at 5–10 g a.i./tree dissolved in 10 L water, applied uniformly around the drip circle. This promotes carbohydrate accumulation, synchronizes floral initiation and reduces vegetative competition (Mishra & Bhatt, 2018; Nair *et al*., 2019)

Stage 2 Pre-bloom (7–10 days before first flower opening): Ethephon at 200 ppm spray to promote uniform flower opening, improve pollen viability and stimulate stigma receptivity (Reddy *et al*., 2016; Kishore & Bhartiya, 1999)

Stage 3 Full bloom to petal fall: BA at 25 ppm + NAA at 50 ppm combined spray to improve fruit set, promote cell division and reduce early flower/fruitlet drop (Thakur *et al*., 2012; Maheshwari *et al*., 2015)

Stage 4 30 days after fruit set: NAA at 40–50 ppm spray to reduce June drop during the critical cell division phase (Rathod *et al*., 2018; Sandhu & Arora, 1992)

Stage 5 60 days after fruit set: GA_3 at 50 ppm spray to promote cell enlargement and improve fruit size (Sharma *et al*., 2014; Sonawane *et al*., 2009)

Stage 6 30 days before expected harvest: Ethephon at 150 ppm spray to promote synchronized ripening, reduce tannin, improve TSS and ensure uniform colour development (Chandramohan *et al*., 2009; Sandip *et al*., 2015)

The above schedule integrates the best practices documented across all reviewed studies and is consistent with general PGR management frameworks established for tropical tree crops (El-Otmani *et al*., 2000; Wertheim, 1998). Timing adjustments are required for different agroclimatic zones, as documented by Singh & Singh (2000) for arid-zone versus humid-tropical sapota production.

Precautions and Limitations:

PBZ must be calibrated to canopy spread; overdose

causes excessive vegetative suppression and reduces yield in subsequent seasons (Chadha & Kumar, 2015). Ethephon sprays must be avoided during high temperature (>35°C) or high humidity conditions that accelerate ethylene release and may cause premature fruit drop (Reddy *et al*., 2016). GA_3 at doses >100 ppm may delay ripening and suppress sugar accumulation (Sharma *et al*., 2014; González *et al*., 1998). Repeated high-dose auxin applications can cause lenticel russeting on fruit skin (Patel & Singh, 2010). All PGR applications must comply with local agricultural regulations and Maximum Residue Limit (MRL) guidelines; residue studies in sapota specifically are noted as a research gap by Patil *et al*., (2011).

Emerging Research Areas and Future Directions:

(i) Precision PGR delivery systems: Encapsulation of PGRs in biodegradable polymers (chitosan, alginate nanoparticles) for controlled release can extend PGR action duration, reduce dose requirements and minimize environmental contamination. Lerner (1999) identified slow-release PGR formulations as a priority research area in stress physiology and this concept is directly applicable to sapota orchard management.

(ii) Molecular breeding and transcriptomics: Identifying sapota genotypes with altered hormonal sensitivity using genomic tools can reduce PGR dependency. Transcriptomic studies during PBZ-induced flowering can identify key transcription factors for marker-assisted selection. The peach floral development transcriptomic framework established by Zhuang *et al*., (2013) offers a methodological template. Williamson & Coston (1990) highlighted the importance of understanding canopy architecture × hormonal balance interactions, which is also tractable through genomic approaches.

(iii) Biostimulant integration: Combining PGRs with seaweed extracts, humic acids, or microbial inoculants can enhance PGR response through improved nutrition and hormonal balance. Babu *et al*., (2011) and Akhter *et al*., (2015) identified biostimulant × PGR synergy as a high-priority area across tropical fruit crops. Initial data from sapota by Kumar *et al*., (2014) suggest 15–20% additional yield gains when seaweed extract is combined with PGR programs.

(iv) Climate change adaptation: Heat stress, erratic rainfall and elevated CO_2 alter hormonal homeostasis in sapota. Brassinosteroid and salicylate-mediated thermotolerance and drought resilience require urgent investigation (Kaur & Singh, 2021; Lerner, 1999). The relevance of polyamine stress-tolerance pathways — reviewed in a sapota context by Mukherjee & Chattopadhyay (2019) — is expected to increase under climate change scenarios.

(v) Residue safety and MRL establishment: Despite increasing PGR usage, systematic residue monitoring data for PGRs in sapota fruit and soil are limited (Patil *et al*., 2011). Residue kinetics, half-life under tropical field conditions and consumer safety data are essential prerequisites for developing MRL regulations. ICAR (2012) and Kader (2002) both emphasize residue management as an integral dimension of PGR-based crop management programs.

Conclusion

This review has comprehensively analyzed the influence of plant growth regulators on flowering, yield and quality of sapota based on 78 research publications spanning 1974–2024. The evidence overwhelmingly demonstrates that exogenous PGR application can substantially overcome irregular bearing, high fruit drop and suboptimal quality in sapota cultivation. Paclobutrazol soil drenching at 5–10 g a.i./tree consistently emerged as the single most effective PGR intervention — maximizing flowering synchronization (up to 94.7% trees in bloom; Mishra & Bhatt, 2018; Nair *et al*., 2019), yield (up to 15.61 kg/tree, representing 118.6% increase over control) and quality (TSS 27.3 °Brix, Vitamin C 21.6 mg/100 g, shelf life 14.2 days). NAA at 100 ppm and ethephon at 200 ppm provided the best results among auxin and ethylene-releasing treatments, respectively, consistent with the early foundational work of Patel & Singh (2010) and the comprehensive yield analysis by Rathod *et al*., (2018). Spermidine at 1.0 mM and 1-MCP at 1.0 µL/L extend shelf life through distinct mechanisms (Mukherjee & Chattopadhyay, 2019; Sharma & Dhaliwal, 2021). Combined PGR treatments generally outperformed individual applications, reflecting the synergistic hormonal regulation documented across multiple experimental systems (Joshi & Verma, 2019; Thakur *et al*., 2012). The integrated six-stage PGR management schedule recommended here draws on studies from diverse agroclimatic zones (Reddy *et al*., 2016; Chadha & Kumar, 2015; Pillai *et al*., 2020) and is designed for direct adoption in commercial orchards. With evidence-based PGR management, sapota productivity could be elevated from

the current national average to 16–20 t/ha, significantly improving farm income and India's position in the global tropical fruit market (NHB, 2022; ICAR, 2012).

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