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Influence of plant growth regulators on propagation techniques of fruit crops: A comprehensive review

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Abstract
Fruit crop propagation is a critical component of sustainable agriculture, influencing global food security and economic stability. Traditional propagation methods, including seed propagation, grafting, and cutting techniques, often face challenges such as low success rates, prolonged juvenile phases, and vulnerability to environmental stressors. The integration of plant growth regulators (PGRs) offers a promising solution to enhance propagation efficiency and sustainability. PGRs, including auxins, cytokinins, gibberellins, and abscisic acid, play a pivotal role in modulating plant growth, stimulating root and shoot development, and improving overall crop resilience. Auxins, such as indole-3-butyric acid (IBA) and naphthaleneacetic acid (NAA), significantly enhance root induction in cuttings, promoting uniform and rapid establishment. Cytokinins contribute to enhanced shoot proliferation in micropropagation techniques, enabling mass production of disease-free planting material. Additionally, gibberellins facilitate seed germination and seedling vigor, expediting the propagation cycle. Integrating these PGRs with modern biotechnological tools, such as tissue culture and hydroponics, further optimizes propagation outcomes while minimizing environmental impact. The application of PGRs in fruit crop propagation supports sustainable agricultural practices by reducing dependency on chemical inputs, increasing propagation efficiency, and mitigating the effects of climate change. This review highlights the role of PGRs in accelerating fruit crop propagation and discusses their potential in fostering resilient and high-yielding cultivars. Advancing research in this domain is essential for developing eco-friendly, cost-effective, and scalable propagation strategies, ensuring food security for future generations.

Keywords: Plant hormone, propagation, micropropagation, application, rooting

1. Introduction

Plant growth regulators (PGRs) are essential in modern agricultural practices, particularly in fruit crop propagation. These naturally occurring or synthetic chemical substances influence various physiological processes, such as cell division, elongation, flowering, fruit development, and stress responses (Singh *et al.*, 2018; Singh *et al.*, 2015) [35, 38, 39, 43, 44, 32, 33, 46, 49]. The strategic application of PGRs enhances the efficiency of fruit crop propagation by improving germination, rooting, flowering, and fruit set. This has significant implications for commercial fruit production, ensuring higher yields, better quality, and improved resistance to environmental stresses (Lawes and Woolley, 2001) [18].

Vegetative propagation is the preferred method for multiplying elite fruit crop varieties while maintaining genetic purity. However, the rooting ability of stem cuttings, shoot multiplication rates, and grafting success are highly dependent on internal and external factors, including hormonal balance (Saroj and Singh, 2020) [28]. The application of auxins, such as indole-3-butyric acid (IBA) and naphthalene acetic acid (NAA), has been widely studied for their role in enhancing root initiation and growth in hardwood, semi-hardwood, and softwood cuttings of fruit crops (Satpal *et al.*, 2014; Chander and Kumar, 2023) [29, 4]. Similarly, cytokinins like benzyl adenine (BA) promote shoot proliferation, while gibberellins contribute to breaking seed dormancy and improving germination rates in fruit crops. Naturally, plants have the ability to produce their own endogenous PGRs. However, the concentration of endogenous PGRs within the plant changes with time, season, and during its developmental stage (Swarts *et al.*, 2018) [53]. Auxins and other PGRs have been shown to enhance rooting capacity and generate high-quality root systems in a number of species (Singh, 2014; Rawat *et al.*, 2014) [36, 37, 47, 24]. the initiation and growth of adventitious roots are significantly regulated by the PGR indole-3- acetic acid (IAA).

Its exogenous application produces a consistent influence on root development. NAA (α-naphthaleneacetic acid) is another commonly utilized synthetic auxin that is suitable for cutting roots and has a beneficial effect on the majority of plant species (Saeed *et al.*, 2021) [27].

Advancements in tissue culture techniques have revolutionized fruit crop propagation, allowing for mass production of disease-free, uniform, and high-yielding plants. Plant growth regulators are fundamental in micropropagation protocols, where cytokinins promote shoot multiplication, auxins induce root development, and gibberellins regulate elongation (Singh and Singh, 2018) [35, 38, 39, 43, 44]. The application of PGRs in *in vitro* propagation has been particularly beneficial for crops with slow or difficult traditional propagation methods, such as bananas, citrus, and apples. Furthermore, somatic embryogenesis and organogenesis, driven by specific PGR combinations, have provided a means to develop new plant varieties and overcome propagation barriers.

2. Application of growth regulators in fruit crop vegetative propagation

2.1 Pomegranate

Singh, (2014) [36, 47] recorded that the maximum number of sprouted cuttings, average sprout length, average number of leaves, percentage of rooted cutting, number of primary roots, and average root length were observed in the 5g. L-1 concentration of IBA among all treatments. Sharma *et al.* (2009) [31] investigated how PGRs affected pomegranate cuttings. The results indicated that IBA 500 ppm + Borax 1% produced the greatest rooting, quantity, and length of roots in both semi-hard and hard wood cuttings. IBA 500 ppm + Borax 1%, IBA 300 ppm + Borax 2%, and IBA 5000 ppm cuttings all maintained their highest field survival rates. Cuttings of hard wood react more favourably to the hormonal treatment than cuttings of semi-hard wood. Mehta *et al.* (2018) [20] reported that the T3 (January 25th) planting period had the highest percentage of rooted cuttings (71.11%), number of sprouted cuttings (7.11), number of sprouts per cutting (4.00), and number of leaves on new shoots (10.89). When it came to IBA concentration, the C1 (500 ppm IBA) treatment produced the greatest number of sprouted cuttings (7.33), number of sprouts per cutting (4.66), length of the longest sprout (7.28 cm), number of leaves on new shoots (10.66), and percentage of rooted cuttings (73.33%). Indole butyric acid, is a synthetic plant hormone. It actively prevents developing shoots' axillary buds from breaking and promotes the initiation of roots. It encourages cell elongation, which helped to the growth of the roots (Singh, 2017).

2.2 Guava

Guava plants can be multiplied by grafting, cutting, budding, layering, inarching, and seeding. However, the best way to propagate this crop is still air-layering combined with exogenous auxin treatment, which stimulates the growth of longer roots. To promote plant growth, particularly producing roots with improved vigor in layering, growth regulators such as IBA have been applied. However, time, rooting media, and environmental factors all have an important effect on auxin effects (Saroj and Singh, 2020; Singh, 2018) [28, 35, 38, 39, 43, 44]. The findings indicated that softwood cuttings treated with paclobutrazol at 1000 ppm solution had the most sprouting (71.22%), the most branches (3.44), the highest root weight (1.46 g), and the best survival (57.22%). In soft wood cuttings treated with IBA at 1000 ppm, the longest shoot (8.24 cm) and the greatest number of roots (59.66) were observed (Ullah and others, 2005) [54]. According to Kareem *et al.* (2016), the IBA (4000 ppm) produced the best results in terms of average root length, number of roots per cutting, and sprouting percentage.

2.3 Grapes

Grape is normally propagated through stem cuttings. Vegetative propagation in fruit crops works faster than seed propagation. Auxin application has been found to enhance the histological features like formation of callus and tissue and differentiation of vascular tissue. Internal factors affecting rooting of cuttings include the amount of stored food in cuttings. (Singh and Chauhan, 2020) [48]. One of the most important components in the formation of rooted cuttings is the rooting media. It is among the elements influencing grape cutting growth and roots. Grapes (*Vitis vinifera*) treated with 4000 mg/l IBA (indol-3-butyric acid) produced the greatest number of roots (Glavi *et al.*, 2013) [12].

2.4 Citrus

Vegetative propagation is used in the commercial production of citrus (*Citrus* spp.). With the exception of India, stem cutting is the most significant vegetative propagation technique worldwide. While the mist house growing condition was found to be efficient in enhancing the cuttings' success rate, the cuttings treated with a high concentration of IBA performed best in terms of rooting and survival percentage (Singh, 2017; Singh and Singh, 2016) [41, 50]. IBA at 100 ppm level produced the highest survival rate (100%) and rooting percentage (100%) among the various combinations examined, and it was determined to be the most effective for inducing citrumelo cuttings to sprout (Fadli *et al.* 2017) [10]. The findings showed that T2C3S2 (December planting time, 600 ppm concentrations of IBA, and semi-hardwood cutting) was the best out of all the treatment combinations. Accordingly, it can be proposed that a semi-hardwood cutting of lemon (*Citrus limon* Burm.), cv. Pant Lemon-1, planted in December following treatment with 600 ppm concentrations of IBA, is a useful method to enhance propagation in the Garhwal Himalayan valley (Satpal *et al.* 2014) [29].

2.5 Apple

The apple (*Malus domestica*) is a woody plant belonging to the Rosaceae family. Root development can be enhanced by applying growth regulators such as IBA and NAA, along with different rooting media. The highest graft height, scion diameter, rootstock diameter, number of leaves per graft, root length, and root diameter were recorded in the combination of the Vance Delicious scion and M-793 rootstock. Factors such as rooting hormones, planting time, stock plant maturity, and propagation environment play a significant role in the successful rooting of stem cuttings (Singh *et al.* 2019) [34, 45]. In semi-hardwood cuttings of MM 106, which produced the newest leaves, followed by M 9 and M 2, Sharma *et al.* (2005) [30] found that IBA 3000 ppm boosted the quantity of roots and the development of new leaves. Apple rootstock MM 106 with trench layering had the highest number of rooted shoots, longest root length, and rooted sprouts with ringing of shoot bases + IBA 2500 ppm (Srivastava *et al.* 2006) [51]. Regarding the impact of propagation techniques on feather production, tongue grafting produced the greatest number, length, and height of feathers in both cultivars, Redspur and Wellspur (Kumar *et al.* 2004) [15].

2.6 Litchi

Litchi can be grown vegetatively through air layering or by seed. One commercial technique for asexual or vegetative propagation is air layering. 50 ppm GA3 had the most panicles per plant (9.34), followed by 30 ppm (GA3), 50 ppm (NAA), 30 ppm (NAA), and 50 ppm (CCC). However, a minimum of 6.55 panicles per plant was noted at 30 ppm (CCC). Therefore, these treatments will be implemented to improve *Litchi* canopy and blooming management (Gaurha *et al.*, 2021) [11]. Exogenous treatment of IBA at 4000 ppm has successfully produced a high percentage of rooting and root characteristics of guava air layers. In terms of layering timing, August 15th provided the best rooting characteristics and success. The highest rooting percentage and root characteristics were obtained by humid sphagnum moss among the rooting media (Rymbai *et al.*, 2010) [26]. The findings showed that litchi orchard soil + FYM + PGPR @ 50g/kg growing media caused growth to emerge earlier after planting (105.98 days) and also produced better results for all the parameters that were examined, such as survival percentage (90.00%), plant height increase (10.65 cm), number of leaves/layer (32.30), average leaf area (25.50 cm2), total leaf area (823.45 cm2), total root length (14.27 m), chlorophyll content (0.91 mg/g), fresh and dry weight of roots (8.17 and 3.08 g), fresh and dry weight of shoots (58.03 and 35.30 g), and root:shoot ratio on fresh and dry weight basis (0.141 and 0.087), respectively (Chawla and Mehta, 2015) [5].

2.7 Phalsa

The phalsa plant can be grown by layering and cuttings, respectively. The type of cutting and the planting timing have a significant impact on phalsa rooting. The optimal time to prepare cuttings and plant them is determined by the plant's physiological state and climate. However, the timing of cutting preparation in phalsa as a whole affected the success of root initiation. It has been discovered that auxin treatment enlarges histological features such as callus formation and vascular tissue division (Singh *et al.* 2020; Singh, 2017; Singh *et al.* 2016; Singh and Singh, 2018) [28, 40, 48, 41, 50, 35, 38, 39, 43, 44]. In terms of rooting percentage, shoot length, root thickening, and leaf sprouting in the shoot, the cuttings treated with IBA 2000 ppm performed the best (Singh and Tomar, 2015; Singh *et al.* 2015: Singh *et al*, 2018) [49, 32, 33, 46]. Devi *et al.* (2016) found that phalsa performed best in terms of shoot and roots when exposed to 300 ppm of IBA solution.

2.8 Apricot

According to Suriyapananont (1987) [52], stem cuttings of Japanese apricot treated with IBA at a concentration of 2000 ppm demonstrated a significant increase in the percentage of rooting and the quality of the roots formed; however, at 1500, 2500, and 3000 ppm of IBA, the quality seemed to decrease, while NAA and IAA did not produce any discernible effects. According to Perez-Tornero *et al.* (2000) [23], a desirable number of shoots of a suitable length for transfer to other subcultures were produced by an IBA concentration of 0.5 to 0.6 mg l–1. Similar percentages and numbers of roots per shoot were induced by IBA and NAA. The highest number of roots per shoot (5.3±0.5) was achieved after inducing 6 mg l–1 of IBA, while the best rooting percentages (92.8±2.5%) were induced in NAA at 2 mg l–1.

2.9 Peach

Using softwood, semi-hardwood and hardwood cuttings, peach plants were propagated by stem cutting (Reighard *et al.*, 1990) [25]. According to data collected on rooting parameters 45 days after planting, Shan-i-Punjab showed the highest levels of rooting measurements, including root length, root thickness, main root length, number of roots per cutting, and root weight, when treated with IBA 3000 ppm (Singh *et al.* 2009). Pathlan, *et al.*, (2022) [22] reported that hardwood cuttings treated with 2400 ppm indole-3-butyric acid for 1 to 2 minutes showed a higher percentage of sprouting, survival, number of roots, number of leaves, and girth. The best results have been obtained with IBA treatments that involve the auxin hormone group. It has been shown that IBA improves hardwood and softwood (Kumari *et al.*, 2018) [16]. Ibrahim *et al.* (2020) [14] reported that the maximum percentage of rooting (40%) was achieved with 2000 mg L-1 IBA. IBA levels, however, had no noticeable effect on callusing. Control produced no rooting or other root characteristics. The effects of IBA concentration on vegetative features, with the possible exception of shoot diameter and leaf number, were similar. The maximum values of shoot diameter (1.12 mm) and leaf number (4.51) were recorded at 2000 mg L-1 IBA.

2.10 Dragon Fruit

Dragon fruit can be propagated asexually by stem cuttings, grafting, and micropropagation, as well as sexual using seeds (Singh and Rani, 2023) [42]. The results of the stem cuttings of dragon fruit treated with IBA, NAA, and their combinations show that the cutting treated with IBA 4000 ppm had the highest length of the longest root (21.33 cm), average number of roots per cutting (41.76), diameter of the root cutting (1.38 mm), fresh weight of the root cutting (2.22 g), and dry weight of the root cutting (0.59 g). This was most likely caused by exogenous auxin's (IBA) simulative effects on the formation of new root tips in stem cuttings (Hernosa *et al.* 2022) [13]. According to a study by Malsawmkimi *et al.* (2019) [19], the shoots treated with 250 ppm IBA concentration accumulated the maximum amounts of nitrogen and protein.

Kiwifruit

Cuttings, budding, grafting, and sexual propagation were among the methods commonly used for the production of kiwifruit (Dutta *et al.*, 2023) [8]. According to Ercisli *et al.* (2002) [9], the 2000 ppm IBA applied to root the SCs of the kiwifruit cultivar *A. deliciosa* was effective. IBA applied at 3500 ppm increased the number of roots per cutting, number of secondary roots per cutting, average root length (cm), and other parameters in comparison to control. The highest rooting percentage of 56.94 was observed at 3500 ppm, followed by 53.61 at 2500 ppm (Ali *et al.*, 2017) [2].

Table 1: Rooting in fruit species stem cutting with PGRs with other chemicals formulation

Cultivars	Type of Stem cutting	Concentration	Method of treatment	References
Morus alba	Hardwood Cuttings	5000ppm IBA	Quick dip	Singh *et al*. (2015)
Morus alba	Hardwood Cuttings	2000ppm IBA	Quick dip	Singh *et al*. (2014)
Pyrus communis	Hardwood Cuttings	2500ppm IBA	Quick dip	Dhand *et al*. (2019)
Prunus domestica L.	Hardwood Cuttings	2500ppm IBA	Quick dip	Lalhal *et al*. (2017)
Ficus carica L.	Hardwood Cuttings	1000ppm IBA	Quick dip	Chander and Kumar, (2023)
Ficus palmata Forsk.	Semi hardwood Cuttings	6000 ppm IBA	Quick dip	Mewar *et al*., (2016)
Dragon fruit	2 to 5 days old shoot	5000ppm IBA	Quick dip	Ayesha and Thippesha (2018)
Sahebi and Soltanin cv. of grape	Shoot apical meristems	1.5 mgL-1 BA	-	Aazami, (2010)
Carissa carandas L.	Hardwood Cuttings	8000 ppm IBA	Quick dip	Dey *et al*., (2017)
Carisa carandas L. Cv. Pant Manohar	Hardwood Cuttings	8000 ppm IBA	Quick dip	Tanuja, *et al*., (2018)
Carissa carandas L.	Semi-hardwood Cuttings	Sucrose-4% + IBA 8000 ppm	Quick dip	Patro *et al*., (2025)

Application of growth regulators in fruit crop micro propagation

Fruit plant micropropagation can multiply genotypes that yield sterile seeds and provide yearround, disease-free plant material with less effort and cost. Over the past 20 years, several research teams have created *in vitro* conditions that are appropriate for the micropropagation of different apple cultivars and rootstock material, including [3-9]. Over the course of four weeks, these *in vitro* propagation techniques typically yield four to six shoots from a single source shoot (the transfer generation). It may take multiple generations to generate enough clonal plants in the interim for this method to be profitable (Lal *et al*., 2022) [71].

***In vitro* rooting**

PGRs like auxins (IAA, IBA, 2,4-D, and NAA), which are frequently thought of as rooting hormones, are in responsibility of producing high-quality roots *in vitro* in plant tissue culture. Only 0.53 M NAA supported the largest roots (average of 7.66 number and length of 22 cm) among the various NAA concentrations evaluated for Golden Delicious apple trees (Renu and Singh, 2018) [70]. On full strength MS media enhanced with 0.5 mg/L IBA, the Gisela 5-clonal cherry rootstock showed the highest *in vitro* rooting (100%) (Sharma *et al*., 2017) [69]. On halfstrength MS medium supplemented with 0.5 mg/L IBA, a one-step approach produced the best rooting (18.20%) (Thakur *et al*., 2016) [68]. *Citrus* shoots were reported to root most effectively in half-strength MS medium containing IBA and NAA (Kour and Singh, 2012) [67]. The highest rooting percentage (83.33), number of roots per shoot (2.47), and longest root (3.57 cm) were shown by IBA (1.0 mg/L) and NAA (1.0 mg/L). Rootstock Ferely Jaspi has the longest roots (3.08 cm), the most shoots (8.1), and 100% rooting (Vujovic *et al*., 2012) [66]. For shoots from BAP medium, the highest percentage (96%) and other rooting parameters, such as root numbers (4.88) and length of the largest root (1.83), were found in half strength MS media supplemented with 5 M IBA and 0.3 M gibberellic acid (GA3) (Ruzic *et al*., 2011) [65].

On MS medium supplemented with 1.0 mg/L NAA and 1.0 mg/L IBA, *Citrus* × jambhiri L. rooted effectively (Saini *et al*., 2010) [63]. IBA can start roots at different concentrations, however MM106 exhibits the highest levels between 2.0 and 2.5 mg/L (Balla *et al*., 2003) [60]. The maximum rooting percentage (10.42%) in Chinese plum without phoroglucinol and 79.76% with it was observed in half strength MS medium supplemented with 0.2-0.5 mg/l IBA, 15 g/L sucrose, and 20-40 mg/L PG (Sharma *et al*., 2007) [62]. On 12 MS media containing 0.1–0.5 mg/L IBA, 2% sucrose, and 0.4% agar in a single step, about 75% rooting was accomplished. Rooting percentage was raised by inducing *Malus seiboldii* genotypes at night with 25 M IBA in liquid or agarized medium (Ciccotti *et al*., 2009) [61]. *Citrus* magaloxpcarpa L. roots were more successfully induced with 0.50 mg/L NAA and 0.25 mg/L BAP (Haripyaree *et al*., 2011) [72]. According to Soni *et al*. (2010) [64], Merton793 rooted more effectively in MS media (1/2 strength) containing 0.1 mg/L naphthyl acetic acid. In apple rootstocks MM111, it was found that micro cuttings were better transferred to auxin-free solid medium after root initiation on half strength MS media containing 0.5 mg/L IBA (Kaushal *et al*., 2005) [59]. Pummelo rooted most effectively in half-strength MS medium containing 1.0 mg/L NAA, it was discovered. In Nagpur Mandarin, IBA alone may induce up to 50% rooting; however, 4.92 M and 1.11 M BAP produced 78% rooting and the highest number of roots per shoot (AL-Bahrany, 2002) [58].

Acclimatization / Hardening

Acclimatization is the process by which *in vitro*-rooted plantlets adapt to their new environment after transplantation. It is crucial for *in vitro* grown plantlets since *in vitro* plant material does not readily adapt to *in vivo* conditions (Lalrinsanga *et al*., 2013) [74]. Certain factors, such as humidity, the potting mixture's composition, pH, and watering schedule, all affect how well a plant adjusts to new conditions. In pots containing an autoclaved mixture of peat (70%) and perlite (12%) and sand (12%) and orchard soil (6.0%) covered with plastic film, *Pyrus elaeagrofolia* grown *in vitro* demonstrated a robust response to acclimatization (Kaur and Chopra, 2003) [73]. The highest survival percentage (93.33) among the various potting combinations was reported in soil + sand + vermiculite (1:1:1) during an experiment on the *in vitro* multiplication of rough lemon (*Citrus jambhiri* Lush.) (Kour and Singh, 2012) [67].

Conclusion

Plant growth regulators play an indispensable role in enhancing the efficiency of propagation techniques in fruit crops. Their influence spans from conventional methods like seed germination, cuttings, and grafting, to advanced tissue culture and somatic embryogenesis protocols. Auxins remain the most critical for root induction, while cytokinins drive shoot proliferation, gibberellins support dormancy breaking, ABA aids in stress tolerance, and ethylene synergistically enhances rooting and callus formation. The integration of innovative technologies such as nano-PGRs, molecular breeding, and bioreactors promises to further refine propagation protocols. A careful balance of PGR type, concentration, and application method is essential to maximize benefits while minimizing risks. Future research should emphasize eco-friendly alternatives and species-specific optimization to achieve sustainable propagation strategies for diverse fruit crops.

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