



Adventitious Root Formation and its Utilization for Sustainable Plant Propagation

Aarushi Gautam¹ and Manu Pant^{2*}

¹Department of Biotechnology, Graphic Era (Deemed to be University)
Dehradun 248 002, India

²Department of Biosciences, Graphic Era (Deemed to be University),
Dehradun 248 002, India

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***Correspondence**

Manu Pant
manupant@geu.ac.in

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Abstract: Adventitious roots arise from non-root organs such as stems, leaves, or floral tissues, thereby enhancing plant growth, development, and survival. Their formation represents an important adaptive response that is triggered by mechanical injury, environmental stress, or other external stimuli. Consequently, adventitious rooting is closely associated with improved plant establishment, stress tolerance, and crop productivity under adverse environmental conditions, including drought, soil salinity, and waterlogging, which are common in arid and semi-arid regions. The initiation and development of adventitious roots are regulated by a complex interplay of phytohormones, particularly auxins, cytokinins, and ethylene, together with transcription factors, signalling pathways, and epigenetic mechanisms. Recent advances in molecular biology have identified several key genes involved in auxin signalling and transcriptional regulation that govern adventitious root formation. This review synthesizes current knowledge on the physiological, hormonal, molecular, and genetic mechanisms underlying adventitious root development and highlights their applications in plant propagation, crop improvement, and sustainable agricultural production. These insights provide a valuable foundation for enhancing plant resilience and productivity, particularly under environmentally challenging conditions.

Key words: Adventitious root (AR), propagation, trees, horticulture, auxin, genetic factors, signalling molecules

Adventitious roots originate from non-root tissues such as stems, nodes, internodes, or leaves, rather than from the primary embryonic root. The formation of these roots is often triggered by environmental stresses or developmental cues hence represents an important adaptive strategy in plants inhabiting extreme environments. Functionally, adventitious roots increase the effective root surface area, enhance anchorage, and improve the capacity of plants to exploit spatially and temporally variable soil resources.

Arid zone ecosystems are characterized by low and erratic rainfall, high evapotranspiration, extreme temperatures, and nutrient-poor soils, making root systems critical for plant survival, growth, and productivity. Consequently, climax vegetation, including drought-adapted shrubs, perennial grasses, and sparse tree species, has evolved specialized root adaptations to cope with these harsh environmental conditions. Among these, adventitious roots enhance root plasticity and ecological resilience by enabling rapid exploitation of transient surface moisture following rainfall and facilitating recovery from sand burial through the restoration of water and nutrient uptake. This adaptive response improves plant persistence in unstable aeolian environments where soil movement and moisture availability are highly variable.

In addition to supporting individual plant survival, adventitious roots contribute to ecosystem functioning by stabilizing soil surfaces, facilitating vegetation establishment, and influencing successional processes. Together with deep taproots that access groundwater and shallow lateral roots that exploit surface moisture, adventitious roots promote efficient resource partitioning and enhance ecosystem resilience under water-limited conditions. Moreover, in stress-prone ecosystems, particularly arid and semi-arid regions, these roots serve a compensatory function when primary or lateral roots are damaged, desiccated, or rendered ineffective by unfavourable soil conditions (Steffens and Rasmussen 2016 a,b) (Table 1).

Prosopis cineraria, the state tree of Rajasthan, is a deep-rooted leguminous phreatophyte capable of accessing subsoil water in regions receiving only 100-600 mm of annual rainfall (Tewari *et al.*, 1998). Although characterized by an extensive taproot system, plants subjected to sand burial or root damage may produce

adventitious roots from buried stem tissues, enhancing water uptake and anchorage. This adaptive response reflects stress-induced root plasticity, whereby environmental cues activate auxin-mediated pathways that promote adventitious root formation and improve plant resilience under desert conditions (Mhimdi and Pérez-Pérez, 2020).

Among the diverse root adaptations exhibited by plants in arid ecosystems, adventitious roots represent an important yet relatively underexplored mechanism for coping with environmental stress. In arid and semi-arid regions, adventitious roots enhance plant adaptability by increasing root plasticity and improving access to transient soil moisture following rainfall events. They also facilitate recovery from sand burial by restoring water and nutrient uptake, thereby enabling plant survival in unstable aeolian environments. In addition to supporting individual plant performance, adventitious roots contribute to soil stabilization, vegetation establishment, and ecosystem resilience through efficient resource acquisition and complement the functions of deep taproots and shallow lateral roots. Furthermore, they serve as a compensatory rooting system when primary or lateral roots are damaged, desiccated, or rendered ineffective under adverse soil conditions (Steffens and Rasmussen 2016 a,b). Despite their ecological significance, the occurrence, functional role, and adaptive importance of adventitious roots in natural arid vegetation have received comparatively little attention. A better understanding of these root traits is therefore essential for elucidating plant adaptation strategies and predicting vegetation responses to increasing aridity and climate change.

Adventitious roots (ARs) are essential for horticultural plants and tree species in vegetative

Table 1. Synthesis of roles of Adventitious roots in arid climax vegetation.

Aspect	Functional Role of Adventitious Roots in Arid Climax Vegetation
Water acquisition	Enhance rapid capture of brief rainfall pulses and efficient exploitation of shallow soil moisture (Li <i>et al.</i> , 2021).
Soil stabilization	Dense root networks bind soil particles, reducing erosion and sand mobility in aeolian landscapes (Danin, 1991).
Vegetative regeneration	Facilitate recovery following root damage, drought stress, or mechanical disturbance (Steffens and Rasmussen, 2016).
Community structure and resilience	Support ecosystem persistence, functional diversity, and stability of climax vegetation under environmental variability (Kirschner <i>et al.</i> , 2021).

propagation, regeneration, and adaptation to different climatic conditions (Bonga *et al.*, 2016). These roots are considered by horticulturists as crucial for developing genetically identical plants from a single parent. The ability to produce new roots from stem cuttings, leaves, or other plant parts is highly valuable from an economic standpoint, especially for forest species, fruit trees, and ornamental plants (Preece and Read, 2005; Díaz-Sala, 2020). As a result, adventitious root formation (ARF) plays a key role in plant propagation research.

Adventitious root formation is typically known to carry out a plethora of functions for plants like ornamentals, vegetables and fruits, which include propagation, anchorage, nutrient absorption and water conduction, and withstanding injury or stress (Geiss *et al.*, 2009). Under the severe abiotic constraints of arid regions, the root system is the primary determinant of plant survival, productivity, and competitive fitness. Climax vegetation, comprising drought-adapted shrubs, perennial grasses, and sparsely distributed tree species, exhibits a wide range of specialized root adaptations that enable persistence under prolonged water scarcity, high temperatures, and nutrient-poor soils. Among these adaptations, adventitious root formation plays a crucial role in enhancing root system plasticity, functional

redundancy, and resource acquisition, thereby improving plant resilience and contributing to the stability and persistence of arid ecosystems (Mhimdi and Pérez-Pérez, 2020). In case of drought-saline conditions, ARF provides a flexible root system and morphological plasticity enabling expansion in less saline soil and constant water availability, contributing to high salt tolerance, ability to grow in saline soils and enabling land afforestation in saline-affected areas (Singh, 1998; Howari *et al.*, 2022). Besides, ARF is an important aspect of cloning and preserving significant germplasm for tree species, particularly those that are challenging to replicate using conventional methods. This makes ARF crucial for the mass production of commercially important plants with increasing demands in indigenous and international markets. These include ornamentals that enjoy a big market as potted plants or cut flowers (Volckaert *et al.*, 2014), and several fruit crops all of which rely on good ARF for propagation as a strategy to increase yield and provide food security (Zheng *et al.*, 2021). One of the vital roles of ARF in forestry is to revive hard-to-root species, which are particularly essential for biodiversity conservation, forest restoration and sustainable resource management (Bonga *et al.*, 2016). Additionally, adventitious rooting facilitates the large-scale production of superior timber and non-timber forest varieties.

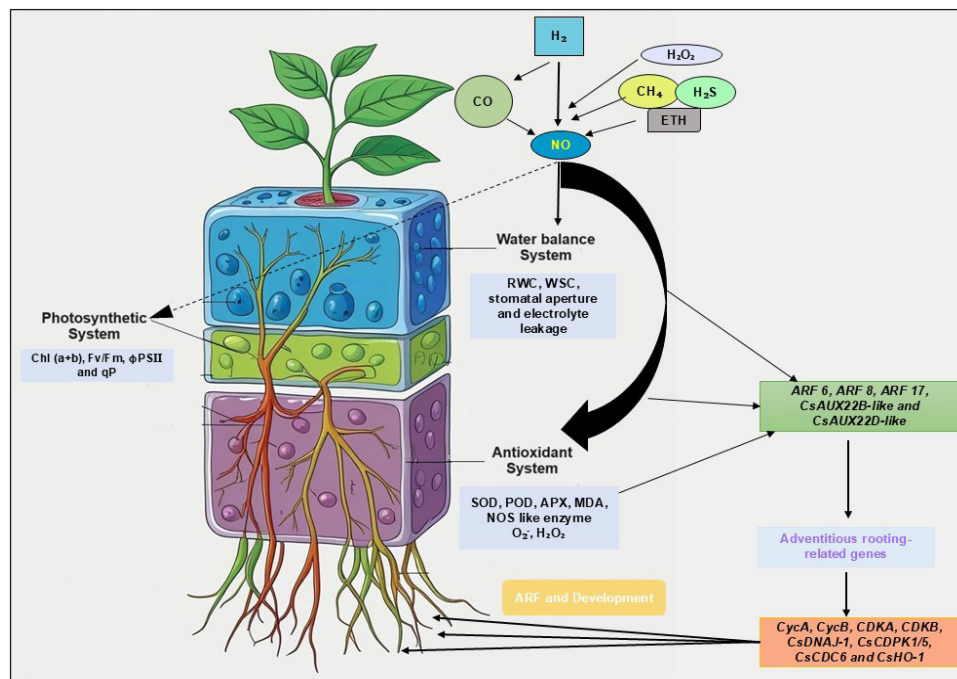


Fig. 1. Interactions among small signalling molecules leading to ARF in plants.

Adventitious roots induction is also associated with factors like wounding or mechanical stress, extrinsic factors, e.g., temperature, humidity, and light intensity, and levels of endogenous hormones (Bonga *et al.*, 2016; Roberto and Colombo, 2020). More recent studies have highlighted the importance of reactive oxygen species (ROS), particularly hydrogen peroxide (H_2O_2), as well as signalling molecules such as nitric oxide (NO) in ARF (Altamura *et al.*, 2023; Roussos, 2023). Further molecular research has enabled deciphering the genetic basis for ARF, wherein the interactions among small signalling molecules that activate ARF genes (Fig. 1), the role of specific genes and transcription factors regulating this process have been explained (Díaz-Sala, 2020).

With the growth of the global horticulture and forestry sector, it becomes increasingly important to characterise and optimise these adventitious rooting processes not only for improving plant propagation methods and enhancing productivity but also to support biodiversity conservation, production of bioactive compounds, and sustainable agriculture. More importantly, the understanding of ARF can be valuable for planned plant production in regions with adverse climatic conditions, which in turn can be harnessed as potential inducers for root development. Despite their ecological importance, adventitious roots in natural arid climax vegetation remain relatively understudied compared to other root traits. Most existing research has focused on crops or mesic ecosystems, with limited field-based investigations addressing the prevalence, initiation triggers, and functional significance of adventitious roots in desert plant communities. Future research should prioritize *in situ* studies integrating root excavation, isotopic tracing of water uptake, and fine-scale ecological measurements to clarify the contribution of adventitious root dynamics to ecosystem persistence under increasing aridity and climate change (Kirschner *et al.*, 2021).

The present review emphasises the significance of adventitious rooting in horticultural plants and tree species, highlighting the advances in molecular and physiological understanding of root initiation, with potential applications in clonal propagation and forestry. A better understanding of ARF could lead to new, more efficient propagation systems as a

solution to the problem of the scarcity of high-quality planting material, while promoting more sustainable horticulture and forestry practices.

Factors Affecting ARF in Plants

External factors

Water, light, oxygen, injury, hormones such as auxins, and temperature are some of the external factors that have been identified to promote ARF (Garrido *et al.*, 1998; Kreen *et al.*, 2002; Sorin *et al.*, 2005; Ahkami *et al.*, 2009; Geiss *et al.*, 2009). Water is the most important factor for ARF in a plant, as stem cuttings need large quantities of water for root development, especially during the early planting stage, since transpiration and physiological activities are dependent on the attachment of the stem to the substrate (Grange and Loach, 1983; Loach, 1988). In some species like *Hibiscus cannabinus*, flooding makes an important contribution where downtime is very poor for ARF (Polthanee *et al.*, 2008). It has also been studied that wilting, a stress response to water, is effective in inducing ARF in some plants to ensure efficient water uptake (Arya *et al.*, 2022).

The development of AR is also influenced by the availability and provision of nutrients and growth regulators in plants (Li *et al.* 2022). Nitrogen is a crucial nutrient for rooting in stem cuttings. Zerche *et al.* (2016) reported that nitrogen availability is significantly critical to the ARF in *Petunia hybrida* cuttings, due to increased availability of total free amino acids. In another study, Dong *et al.* (2022) showed that nitrogen availability in sweet potatoes significantly enhanced the ARF by promoting cambium development. One of the most common methods of propagation through cutting, especially for the difficult-to-root species, is through the administration of plant growth regulators from outside (Polat and Kamilolu, 2007; Pacurar *et al.*, 2014). Of the different plant growth hormones, auxins have been established as the “rooting hormones”. External applications of auxins like Naphthalene acetic acid (NAA), Indole-3-butyric acid (IBA), and Indole-3-acetic acid (IAA,) have been shown to govern the ARF in the cuttings of many horticulture species (Pop *et al.*, 2011; Pant *et al.*, 2022). IBA is the most commonly used promoter of ARF through conversion of IBA to IAA and is often utilised

Table 2. Effect of exogenous application of hormones on woody and ornamental plants

Exogenous hormone	Species	Propagation methods	Effect on Plants	Reference
IBA	<i>Castanea sativa</i>	Tissue culture	Better root formation in presence of IBA	Vielba <i>et al.</i> (2020)
IBA	<i>Castanea dentata</i>	Tissue culture	Better root formation in presence of IBA	Vielba <i>et al.</i> (2020)
IBA	<i>Castanea sativa</i> × <i>Castanea crenata</i>	Tissue culture	Better root formation in presence of IBA	Vielba <i>et al.</i> (2020)
IBA	<i>Azadirachta indica</i>	Tissue culture	High rate of rooting observed in culture medium containing IBA when compared to NAA	Quraishi <i>et al.</i> (2004)
NAA	<i>Robinia pseudoacacia</i> -148	Tissue culture	Exogenous application of NAA stimulated 310 genes that have a significant role in ARF	Munir <i>et al.</i> (2021)
IBA	<i>Vitis species</i>	Tissue culture	Exogenous application of IBA and NPA promoted ARF	Chang <i>et al.</i> (2022)
IBA	<i>Malus</i> × <i>domestica</i> Borkh.	Tissue culture	<i>mdm-MIR393b</i> mediated ARF upon external application of IBA	Li <i>et al.</i> (2021)
IAA	<i>Eucalyptus grandis</i>	Tissue culture	External application of IAA restored rooting ability; rooting percentage increased 4.7 fold	de Almeida <i>et al.</i> (2015)
	<i>Robinia pseudoacacia</i> L.	Tissue culture	ARF is dependent upon external application of IBA, ARF initiation observed at 72 HAE	Uddin <i>et al.</i> (2022)
IBA	<i>Cedrela fissilis</i> Vellozo	Tissue culture	External application of IBA initiated ARF	Ribiero <i>et al.</i> (2022)
GA ₃	<i>Prunus avium</i>	Cutting	GA ₃ pre-treatment enhanced ARF, adventitious rooting percentage in cuttings upto 85%	Ford <i>et al.</i> (2002)
NAA	<i>Pinus banksiana</i>	Cutting	NAA treatment promoted rooting in stem cuttings	Browne <i>et al.</i> (1997)
IBA	<i>Olea europaea</i> 'Manzanilla'	Hardwood cutting	Application of exogenous IBA at 3000 ppm resulted in increased root number, percentage of rooted cuttings, root: shoot fresh weight and branch length	Khajehpour <i>et al.</i> (2014)

in clonal propagation (Wei *et al.*, 2014). A study by Kroin *et al.* (2016) showed that effective ARF in rose cuttings, could be obtained by dipping (brief dip, spray dip, total immersion treatment, prolonged soak, dry dip) the cuttings in auxin solutions depending on the type of stem cutting (either woody or juvenile) (Kroin, 2016). More recent studies have further supported the imperative use of auxins for plant cuttings like in *Camellia sinensis* (Wei *et al.*, 2019) and *Cyclocarya paliurus* (Tian *et al.*, 2024).

While exogenous hormones have been known to enhance ARF in plants due to alterations in endogenous hormone levels (Zhao *et al.*, 2022), it is important to standardise their concentration and treatment since endogenous levels of plant hormones also contribute to total auxin content in the plant body. This is supported by previous studies where the effect of both exogenous and endogenous hormone concentration proved to be significant in determining ARF. Bai *et al.* (2020) showed that the first application of IBA on apple

rootstock cuttings encouraged the development of root primordia, but an extended treatment with IBA elicited ethylene production that inhibited root elongation. A similar effect was reported in *Cedrela fissilis* where endogenous IAA content played a prominent role in ARF in micropropagated shoots (Ribeiro *et al.*, 2022).

Table 2 depicts the promising results of the application of exogenous hormones such as IBA, IAA, and NAA in promoting ARF in plants on cuttings and in tissue cultures. Besides these factors, injury, wounding and drought conditions in arid regions contribute to the formation of ARF in ornamental plants, trees and crops. The activation of some specific genes enhances the synthesis and release of auxins and cytokinins at the injury point, leading to root formation (Creelman *et al.*, 1990; Castro-Camba *et al.*, 2024a; Schillmiller and Howe, 2005). ARF in arid region trees and crops further enables them to withstand harsh climatic conditions like drought and salinity stress by undergoing morphological changes

to maintain the growth and development of plants. Plants of arid regions rely heavily on ARs to withstand harsh climatic conditions. *Opuntia ficus indica* (cactus pear) is valued for its fruits, as fodder, vegetables, and can tolerate severe dry conditions (Nefzaoui, 2009). ARF in cactus pear aids in stress resilience during drought conditions or injury and aids in sustainable production and utilization of the plant. *Pennisetum glaucum* (pearl millet) is considered a staple of the arid and semi-arid regions of India and Africa and is more susceptible to drought stress during flowering and grain filling stages, leading to lower yield (Rao *et al.*, 2000). ARF induction in pearl millet ensures continuous nutrient and moisture availability, thus maintaining growth and grain production in water-scarce arid regions, making it a drought-resilient staple crop of the arid and semi-arid regions (Vadez *et al.*, 2012).

It is the most cultivated and ecologically valuable leguminous crop adapted to withstand arid, semi-arid and usar lands (Kalia *et al.*, 2014). The crop possesses the ability to grow in sandy to saline-alkaline soils, eroded hill slopes and wastelands making it versatile for adverse conditions.

Internal factors affecting ARF in plants

Internal factors such as genetic, physiological, and molecular aspects predominantly control the development of ARs. Both age and the developmental stage of a plant determine the success of ARF. According to Wang *et al.* (2019), a study on the effect of different developmental stages on ARF in *Taxodium 'Zhongshanshan'* tree species showed that juvenile tissues responded better to auxin treatment. The higher ARF competency in juvenile plants as compared to mature tissues can be attributed to the fact that the regenerative capacity decreases with maturity (Kumari *et al.*, 2022). The genetic factors for ARF predominantly refer to the genes for auxin response factor, lateral organ boundary, initiation of root apical meristem, quiescent centre maintenance, homeostasis, and transport of auxin within the plant body are associated with AR and auxin synthetic mechanisms in a plant (Guilfoyle and Hagen, 2007; Li, 2021). Transcription factors (TFs) also play an important part in the ARF. TFs such as Auxin Response Factor (ARF) and AP2/ERF are vital in monitoring auxin and jasmonic

acid (JA) signalling, which in turn is crucial in ARF (Devi *et al.*, 2021; Du *et al.*, 2024). WOX (WUSCHEL-related homeobox) gene family has been shown to regulate cell state and root initiation at the site of wound or injury (Hu and Xu, 2016). A latest study on ARF in mulberry cuttings reported that the application of IBA significantly initiated AR with 18 TFs identified as key regulators in response to IBA (Dou *et al.*, 2024).

Besides the genetic factors, some signalling molecules are also involved in ARF in plant species. There are many physiological processes in which nitrous oxide (NO), hydrogen peroxide (H₂O₂), and ethylene act as signalling chemicals (Fig. 2) and are responsible for the emergence of ARs. These chemicals influence and interact with each other and other components. Some processes, such as those dealing with hormone control, cellular reactions toward stress, and tissue development, are all influenced by these signalling molecules and shape them for ARF. Gaseous signalling molecule nitrous oxide (NO) plays a significant role in a plethora of physiological functions like growth regulation, stress responses, and root development in plants. It has been reported that NO covalently attaches to the side chain of cysteine (S-nitrosation) in proteins that regulate transcriptional and post-translational modifications involved in plant development (Druege *et al.*, 2016; Kushwaha *et al.*, 2019; Niu *et al.*, 2019; Wang *et al.*, 2013). NO alters gene expression, oxidative stress responses, and signalling of hormones that have both direct and indirect roles in ARs. It encourages ARs by promoting auxin signalling, enhancing root primordia cell division and interacting with ethylene (Roussos *et al.*, 2023). Niu *et al.* (2019) reported that upon the application of S-nitrosoglutathione (GSNO), the levels of NO subsequently increased and S-nitrosoglutathione reductase (GSNOR) activity decreased, which resulted in the enhanced ARF in cucumber. A subsequent study (Niu *et al.*, 2023) confirmed that NO facilitated ARF in cucumbers under cadmium stress by improving antioxidant activity, maintaining polyamine activity and regulating the glycolysis pathway.

Hydrogen peroxide (H₂O₂), a reactive oxygen species (ROS), is another major signalling molecule that regulates root development and stress responses involved in ARF. H₂O₂

acts as a secondary messenger molecule in signalling routes that initiate ARF and is generally triggered by wounding or other environmental stimuli. The main function of hydrogen peroxide is to monitor cell-wall remodelling and promote new root primordia regeneration. H_2O_2 has also been recognised as a downstream messenger of auxin signalling during root primordia formation in mung bean seedlings (Liao *et al.*, 2009; Li *et al.*, 2017). In marigold plants, ARF was enhanced upon the application of H_2O_2 as it stimulated the Ca^{2+} and calmodulin (CaM) levels that are closely associated with efficient rooting response and acted as downstream signal molecules of H_2O_2 -induced adventitious rooting (Liao *et al.*, 2012). There have been important studies that implicated the role of H_2O_2 in modulating the effect of stress (by drought or injury) for ARF. It has been reported that H_2O_2 also helps intermediate auxin signals hence, modifying ARF via MAPK and cGMP pathways (Druege *et al.*, 2016; Kang *et al.*, 2018).

Ethylene is another gaseous plant hormone that plays an important role in numerous developmental processes in plants. Among these, adventitious rooting is more pronounced, especially under stress conditions. Ethylene is synthesised in response to physical injuries such as wounds and flooding and influences cell differentiation, elongation, and root

initiation, which coordinate responses in the plant. Accumulated at the damaged sites of a plant's tissue, it supports ARF. The interaction between ethylene and auxin and the regulatory pathways involved in their interaction are vital to ARF in plants (Castro-Camba *et al.*, 2024b; Sun *et al.*, 2024). Several reports have inspected that IBA and ethylene help in ARF in various plants, but the results have been contradictory with positive and negative effects (Yin *et al.*, 2011; Druege *et al.*, 2016; Lakehal and Bellini, 2019). Bai *et al.* (2020) reported that 13 types of differential expressed genes (DEGs) were involved in ethylene synthesis and signal pathways. Genes MdACO and MdACS involved in ethylene synthesis were upregulated in the presence of IBA, leading to the enhanced development of adventitious roots in apple rootstocks.

Application of ARF in plant production

Adventitious roots are indeed indispensable to ornamental, vegetables, and timber species propagation, among many other benefits that adventitious roots have for horticultural industries. Vegetative propagation is a way of propagating through adventitious rooting, which can be useful to maintain the ornamental features of a plant, such as flower colour and plant shape, in a given plant species. Certain auxin treatments have been found to increase rooting percentages that are very essential for

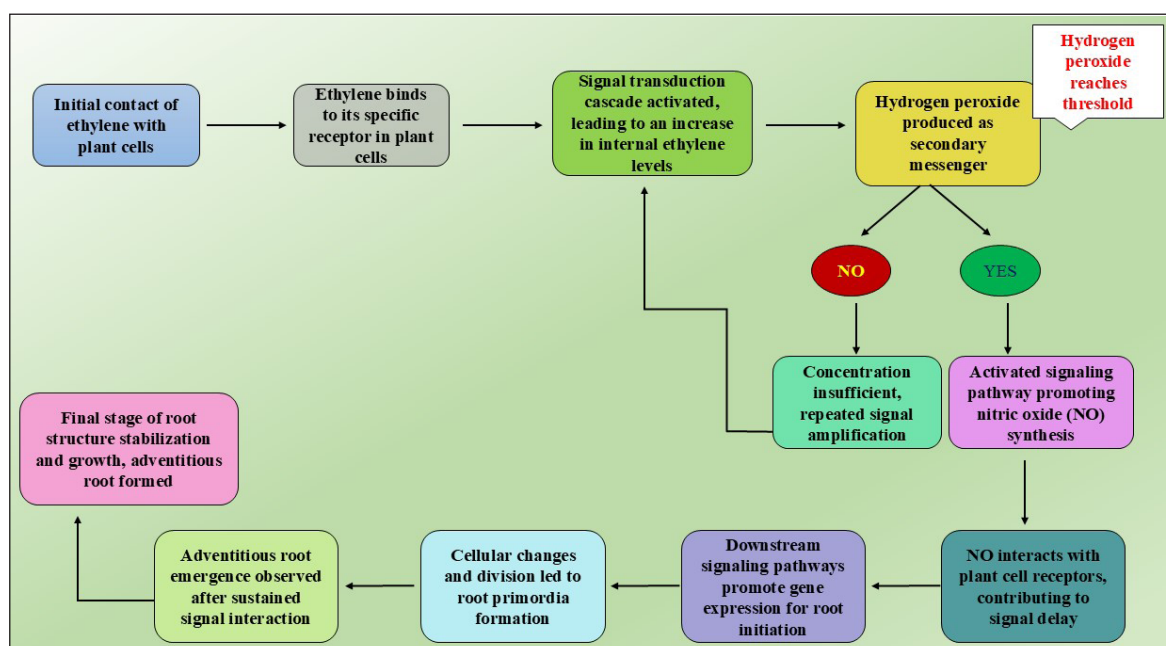


Fig. 2. NO, H_2O_2 , and ethylene crosstalk for ARF in plants.

commercial propagation (Kong *et al.*, 2020; Jafari *et al.*, 2022). In vegetable crops the yield and quality can be enhanced through ARF as they can be propagated rapidly and efficiently with better characteristics as desired by the consumer.

Ornamentals: ARF is mostly preferred to propagate ornamentals due to its enhanced ability to mass propagate through cuttings. According to Ferus *et al.* (2017), rhododendrons are propagated through stem cuttings, which is restricted due to poor root development. However, through ARF, the rooting in rhododendrons cuttings could be improved significantly. Similarly, the propagation of *Chrysanthemum indicum*, one of the most sought-after ornamental species in the horticulture industry, is difficult through cuttings due to poor root formation. However, with the induction of ARFs, the apical stem cuttings can be easily rooted, ensuring higher rate of mass propagation (Ghimire *et al.*, 2022). According to Huang *et al.* (2022), the study on mechanism of ARF during propagation of *Bougainvillea buttiana* 'Miss Manila' showed that endogenous hormones like indole-3-acetic acid (IAA), abscisic acid (ABA), gibberellic acid (GA₃), zeatin-riboside (ZR) which included peroxidase (POD), polyphenol oxidase (PPO), and IAA-oxidase (IAAO) activities, the reduction in the activity of POD, PPO and IAAO led to the increased levels of endogenous IAA and ABA which further triggered ARF.

Vegetable crops: The outgrowths of ARs also provide many advantages in vegetable production and propagation by greatly reducing the propagation time needed for normal seed propagation and facilitating generation of new plants rapidly from cuttings. Studies have shown that greater ARF imparted better crop productivity, stress resistance, disease tolerance, and propagation techniques in vegetable crops. Srikanth *et al.* (2016) reported the ARF formation in stem segments in *Brassica* species in an aeroponics system devoid of plant hormones which aids in fulfilling the demands of leafy vegetables worldwide. The stimulation of ARs can also increase nutrient and water absorption by the root system and consequently, coordinate the general health of the crop as well as yield. It has been indicated that ARF has improved the stress tolerance of the crops by droughts, salinities, and extreme

temperatures. According to Li *et al.* (2016), most of the cucumber plants during drought stress resulted in the production of ABA-induced ARs due to the presence of H₂O₂, increasing plant survival and water retention.

Tree species: ARF in trees serves to improve mass propagation of clones and stress-resistance characteristics. Studies have also indicated the tremendous ecological restoration, productivity and survival outcome of trees in this biological process. ARF ensures cloning of the attributes like quality of the wood, disease resilience and growth rate in the developed plantlets, turning out to be a boon for species where conventional methods of seed generation are time-consuming or impractical. In *Populus* cuttings, ARs were found to facilitate superior clonal propagation (Bannoud and Bellini, 2021) which can be applied for timber and bioenergy uses. Similarly, in *Eucalyptus urugrandis* clones, ARs were developed through the application of AIB and ANA auxins and led to the establishment of high-yield clones that led to higher survival percentages, ultimately leading to the advanced clonal propagation techniques (Patiño *et al.*, 2022). *Acacia senegal*, commonly known as the gum Arabic tree, is an economically important species from arid regions, valued for its gum, which is used in cosmetics, food, pharmaceuticals and beverages is usually found (Upadhyay *et al.*, 2025). ARF in this species is usually induced due to environmental stressors like drought, soil disturbance or mechanical injury, which enables the tree to grow efficiently in dry, nutrient-deficient soils, leading to uninterrupted growth and transpiration. ARF optimizes water intake by maintaining open stomata and canopy activity even in drought conditions (Gehlot *et al.*, 2014; Uni *et al.*, 2023). Besides cutting, grafting is an important vegetative propagation method by which trees acquire disease resistance, vigor and adaptation to environments. For the success of grafting, grafted rootstocks must develop new roots after grafting to support the scion. Consequently, ARF becomes crucial for the success of grafts

ARs also serve as one of the mechanisms that enable trees to resist different biotic and abiotic stresses, by forming roots to survive drought, salinity, waterlogging, and nutrient deficiency. In some cases, high salt tolerance in tree species has been associated with increased ARF. Adventitious roots improve nutrient and

water absorption in the soil, thus reducing the negative effects caused by saline soils. *Mangrove* trees have been defined as having salt tolerance with adventitious roots because of the improved nutrient uptake from saline environments, which enables trees to be healthy despite adverse conditions (Srikanth *et al.*, 2016; Pant and Singh, 2021). Pneumatophores are modified roots typically formed in mangroves like *Avicennia* (black mangrove), *Laguncularia* (white mangrove), *Rhizophora* and *Sonneratia* (red mangrove) and in non-mangrove wetland trees like *Taxodium distichum* (bald cypress) and *Nyssa aquatica* (water tupelo). Pneumatophores not only facilitate oxygen but also play an integral role in supporting biodiversity, maintaining wetland ecosystems, and carbon sequestration. A study conducted on *Avicennia germinans* (Salas-Rabaza *et al.*, 2024) showed that CO₂ effluxes from pneumatophores were highest at the sediment-air, lowest at water-air interfaces and overall CO₂ effluxes decreased when the salinity in the soil decreased during rainy seasons.

Grasses: Among the grasses of the Rajasthan desert, *Cenchrus* species (e.g., *C. ciliaris*, *C. setigerus*) are perennial, C4 bunchgrasses adapted to xeric conditions. Although specific studies on adventitious root formation in *Cenchrus* under natural desert conditions are limited, morphological surveys indicate that these grasses possess fibrous root systems with numerous post-embryonic roots originating from stem bases and nodes, facilitating rapid capture of sparse soil moisture and contributing to rangeland stability. In monocots like grasses, many of these post-embryonic roots qualify as adventitious or crown roots, which originate from stem nodes below the soil surface and enhance water and nutrient uptake over a broad shallow zone, complementing deeper soil moisture acquisition by woody species. These extensive adventitious root networks in perennial grasses not only improve drought resilience but also promote soil binding and reduce wind erosion on sandy plains and interdunal areas, contributing to the overall stability of climax vegetation.

The interplay between deep taproot systems of trees like *P. cineraria* and the dense adventitious and fibrous root matrices of grasses such as *Cenchrus* stabilizes soil structure, moderates sand movement, and

creates microhabitats that support associated angiosperm and shrub species in the climax plant community. Such root architectural diversity fosters partitioning of water resources across vertical soil gradients — deep root systems tap persistent moisture reserves, while adventitious roots and fibrous systems rapidly respond to transient wetting pulses from episodic monsoon rains. This complementarity underpins the resilience of arid zone vegetation to harsh climatic regimes and episodic disturbances such as sand burial or grazing pressure (Tewari *et al.*, 1998).

Conclusion and Future Scope

ARF is essential to for propagation of plants, especially priority species. The benefits include simple methodology, rapid root formation from non-root tissues for quick and consistent plant growth, and production of elite quality, genetically homogeneous plants from selected parents. ARF in ornamental plants ensures mass production of commercially important varieties, thereby assisting to cater to the market demands in floriculture trade. It is a crucial technique for improving food security in vegetable crops by accelerates the development of high-yielding disease-resistant plants. In propagation of tree species, ARF guarantees the effective formation of disease-free rootstocks which are necessary for grafting and the development of strong healthy trees. The modification and improvement of AR through genetic and hormonal regulation have the potential to open up new vistas for more effective and sustainable plant production. In order to overcome obstacles like slow root development, rooting success and environmental stress factors, the use of biotechnological methods like gene editing, tissue culture and plant growth regulators may improve the rooting process. With diligent research, ARF can be maximized to enhance stress tolerance, plant growth and overall agricultural and environmental results by utilizing cutting-edge technologies. In order to address the growing demand for climate-resilient, higher-yielding trees and crops, ARF will be at the forefront of efforts.

Despite their central role in plant adaptation, studies explicitly quantifying adventitious root distribution, initiation triggers, and functional contributions within natural desert

vegetation remain scarce in the Indian context. Future research combining field-based root excavations, isotopic water uptake tracing, and fine-scale ecological measurement can advance understanding of how adventitious root dynamics contribute to ecosystem persistence amidst increasing aridity under climate change.

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Declarations

The authors have no competing interests.

Author's Contributions

Aarushi Gautam: writing original draft and compilation; Manu Pant: conceptualization, compilation and editing

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About the Author

Aarushi Gautam is a researcher in plant biotechnology whose work focuses on plant tissue culture, orchid biotechnology, medicinal plant propagation, nanobiotechnology, and sustainable bioresource utilization. Her research primarily focuses on developing efficient *in vitro* regeneration protocols for economically important and threatened plant species, as well as on biodiversity conservation. She has contributed to the field of plant sciences by securing patents and has authored various book chapters and review articles. She has presented her work through oral and poster presentations at various International and National Conferences and received awards for the same. Her research interests encompass *in vitro* propagation and conservation of medicinal plants, with particular emphasis on adventitious root induction for large-scale production of elite planting material and bioactive compounds. She has worked on optimizing regeneration systems to enhance rooting efficiency and biomass production in medicinal species. Her research aims to integrate biotechnology, nanotechnology and sustainability science to advance plant conservation, floriculture, medicinal plant improvement and climate-resilient agricultural systems.

Manu Pant is an academician and researcher in the field of sciences. Her research expertise encompasses medicinal plants, ornamental crops, and indigenous species, with a strong emphasis on applied plant sciences and biodiversity conservation. Dr. Pant has served as a Research Fellow at the well-known organization, Forest Research Institute (FRI) and the Indian Council of Forestry Research and Education (ICFRE), contributing to nationally funded projects that address ecological sustainability and plant resource utilization. Her work has been supported by state and national level government agencies and recognized through national awards for scientific excellence. She has authored numerous peer-reviewed international publications, secured patents, and disseminated her findings through keynote lectures, invited talks, and presentations at leading scientific forums worldwide. In addition to her research contributions, Prof. Pant has played a pivotal role in organizing national and international conferences, seminars, and training programs, thereby advancing discourse in plant sciences. As an academic mentor, she supervises doctoral, postgraduate, and undergraduate research across diverse domains of plant biology, fostering innovation and scientific inquiry. Her commitment towards advancing knowledge has been acknowledged through appreciation from state and national bodies, underscoring her impact on both scientific research and academic leadership in the field of plant sciences.