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Nursery evaluation of popular apple cultivars under mid hill conditions of North-Western Himalayan region

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ABSTRACT

Apple (Malus × domestica Borkh.) is the most valuable and leading commercial temperate fruit in the North-Western Himalayan region. The performance of apple cultivars and rootstocks is critical for determining a productive orchard system. Almost all rootstock research is focused on orchard results, but there is very little research done in the nursery performance of various cultivars. So, this experiment aims to evaluate propagation efficiency, growth characteristics, and quality parameters of different apple cultivar-rootstock combinations during the nursery phase. Eleven different apple cultivars grafted on seedling rootstocks were evaluated under nursery conditions using a Randomised Complete Block Design (RCBD) with three replications and vegetative attributes such as graft success, plant height, radial growth, leaf area, root metrics, and overall plant marketability were assessed. During the investigations Gale Gala (T_{10}) cultivar of apple had recorded maximum graft success (95.97 %), survival per cent (94.50 %), chlorophyll content (2.65 mg/g), healthy (88.83 %) and saleable plants (78.67 %) while Chelan Spur (T_5) had recorded maximum scion (10.56 mm) and stock diameter (10.90 mm) whereas minimum scion (9.38 mm) and stock diameter (9.76 mm) was measured in King Roat (T_8). Leaf area and number of leaves per plants were recorded highest in Royal Delicious (T_1) i.e. 34.48 cm^2 and 45.00, respectively. From the investigations conducted it was observed that Gale Gala had induced largest vegetative growth variables under nursery conditions that create the essential biological foundation for successful orchard establishment than other cultivars of apple, whereas King Roat performed the poorest. The study encountered variability in seedling rootstock performance due to fluctuating nursery microclimatic conditions. Despite these constraints, careful experimental management ensured reliable evaluation of cultivar performance and provided systematic, comparative information on the performance of different apple cultivars grafted on seedling rootstock under nursery conditions, a stage that is often overlooked despite its critical role in orchard success.

Keywords: *Malus × domestica Borkh, seedling rootstock, propagation efficiency, growth characteristics, quality parameters, saleable plants, plant marketability, orchard establishment*

INTRODUCTION

Apple (*Malus × domestica* Borkh.) is the most valuable and leading commercial temperate fruit in the North-Western Himalayan region and is a member of the Rosaceae family. The states like Jammu and Kashmir, Himachal Pradesh and parts of Uttarakhand are the main apple-growing areas and is the core sector of the economy in these states. Horticulture is the prime mover of economic growth in Himachal Pradesh and the state has also craved and a niche as a horticulture state and is also known as 'Fruit Bowl of Nation' [35]. In terms of income, the apple is the most profitable temperate crop.

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The commercial apple industry in Himachal Pradesh is nearly 60 years old and comprises predominantly of the delicious group, which constitutes 90 per cent of the varieties grown.

The nursery plants are said to be the foundation on which orchards are built, since the success in fruit growing depends upon the quality of planting material used for establishing the orchard. As a result, the availability of high-quality nursery plants is a must in order to satisfy the enormous demand for nursery plants. Apple trees are usually propagated on rootstock rather than on their own roots, because rootstock has numerous advantages. The rootstock has a significant impact on the development, precocity and cropping of scion cultivars grafted on it, as well as conferring resistance to scion cultivars against biotic and abiotic factors. Plants raised on seedling rootstocks are long-lived, have extensive and strong root system with wide and deep distribution in the soil, which accounts for persistent and adequate annual growth of absorbing roots, thus helping them acclimatise easily in the environment.

In Himachal Pradesh, seedling rootstock is the most popular and widely used apple rootstock due to its hilly terrain. On seedling rootstock, plants are multiplied through bench grafting with the scion of desired cultivars. In hilly areas with short growing seasons, nursery plants develop slowly over a period of 6 to 7 months and a significant percentage of them do not reach their full potential at the end of the season. Furthermore, the majority of apple orchards in Himachal Pradesh are located under marginal and unfavourable conditions in respect of climate, altitude, topography, soils etc. and apple cultivation is carried out mostly on sloppy and marginal lands and almost entirely under rainfed conditions. Therefore, the orchardists still prefer the desired varieties of apple on seedling rootstock.

Vegetatively propagated apple rootstocks are released in different countries and have their own quality parameters and often exhibit unequal performance in other countries [36], mainly due to ecological conditions. The choice of rootstock or of the rootstock/cultivar combination is important, not only in the orchard, but also in the propagation fields. Almost all rootstock research is focused on orchard results, but there is very little research done in the nursery performance of various cultivars. Some trials have recently been set up in countries with their own rootstock breeding programmes [12]. So, keeping in mind, the above facts, the present investigation was carried out to study the propagation efficiency, growth characteristics, and quality parameters of different apple cultivars grafted on seedling rootstocks in the nursery.

MATERIAL AND METHODS

Experimental Site and Treatment Details

The field investigation was conducted at the Experimental farm of the Department of Seed Science and Technology, Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, H.P., India, during 2019-20 and 2020-21. The site is located at an elevation of 1020 meters above mean sea level, at 30°51'08'' N latitude and 77°11'09'' E longitude (Figure 1). Meteorological parameters including rainfall, maximum and minimum temperatures, and relative humidity were recorded at the meteorological observatory of the Department of Environmental Sciences, Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) during the cropping period (Jan-Dec, 2019-20 and 2020-21), and these data are presented graphically in Figure 2 to provide context for the environmental conditions experienced during the study.

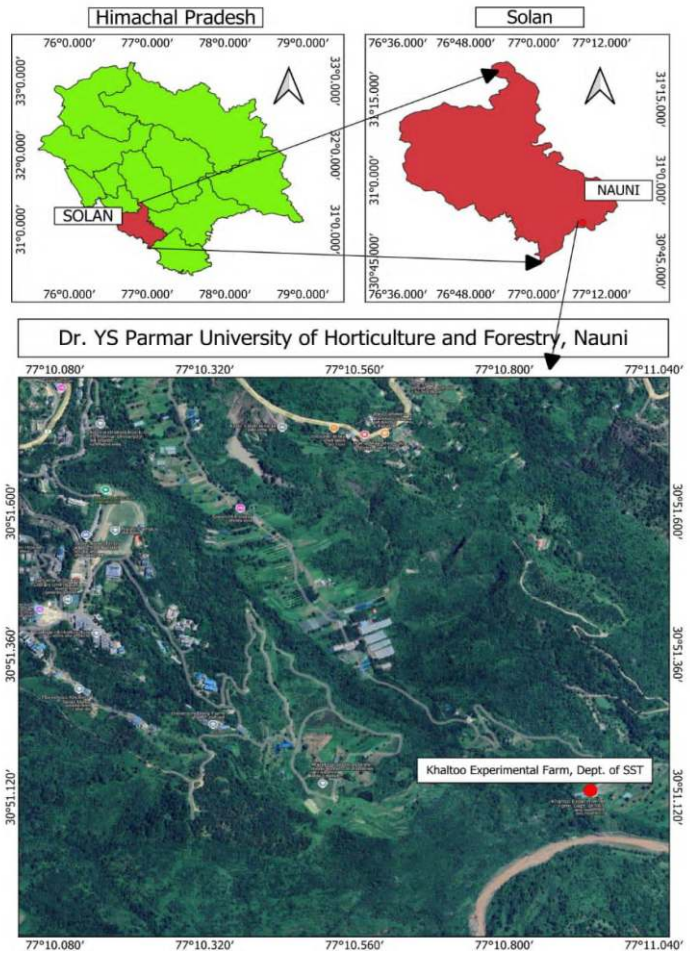
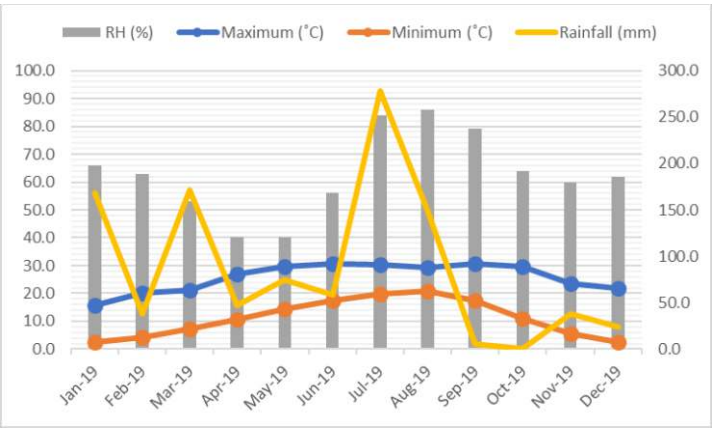


Fig 1. Location of Khaltoo Experimental Farm (The study area map was created with QGIS)

One-year-old uniform seedlings of pencil thickness were selected and planted during first week of January. The roots of the seedlings were slightly trimmed and dipped in Bavistin solution (0.3 %) for fifteen minutes. Then after half an hour seedlings were planted in the beds of 2 1 m at a spacing of 15 cm from seedling and 30 cm from row to row. After planting the beds were immediately given light irrigation. The budwood of different varieties were procured from Department of Fruit Science, Soil Science and different Research Stations of the University of Horticulture and Forestry Nauni, Solan (H.P). The bench grafting was initiated from 21st February onwards with the scionwood of different cultivars having 2-3 intact buds. The field experiment was set up with 11 different apple cultivars divided into 4 different bearing and fruiting groups of apples using a Randomised Complete Block Design (RCBD) with three replications. Various parameters such as propagation efficiency (Per cent sprouting, per cent graft success), growth characteristics (plant height, stock & scion diameter, number of leaves/ plants, leaf area, chlorophyll content, root length & weight) and quality parameters (Per cent survival, per cent healthy plants, per cent saleable plants) were recorded. The data were analysed using analysis of variance (ANOVA) based on RCBD, and the results were considered significant at the 5% level [24].



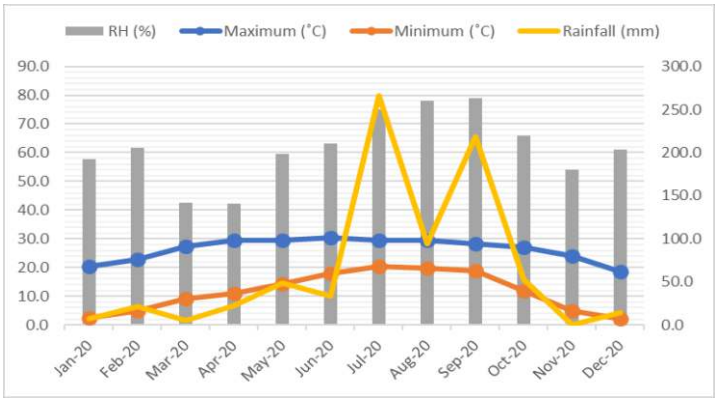
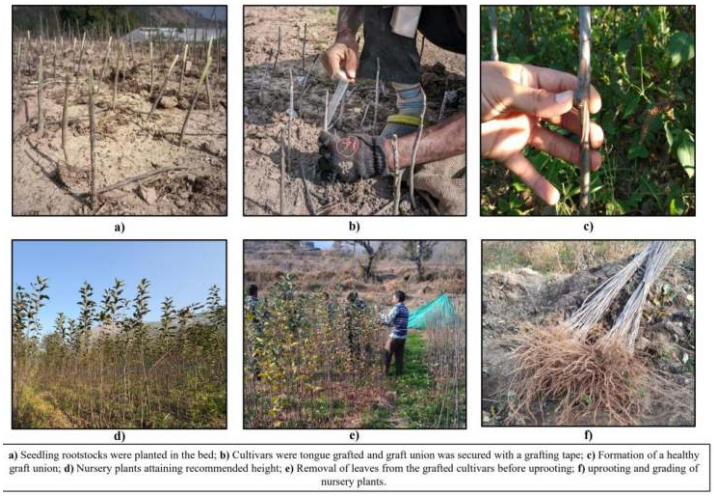


Fig 2. Monthly meteorological data of rainfall (mm), max & min temperature (°C) and relative humidity (%) in the cropping season of 2019-20 & 2020-21



a) Seedling rootstocks were planted in the bed; **b)** Cultivars were tongue grafted and graft union was secured with a grafting tape; **c)** Formation of a healthy graft union; **d)** Nursery plants attaining recommended height; **e)** Removal of leaves from the grafted cultivars before uprooting; **f)** uprooting and grading of nursery plants.

Fig. 3. Nursery operations performed during investigations.

RESULTS AND DISCUSSION

Per cent sprouting: The perusal of data (Table I) reveals that The Gale Gala (T_{10}) cultivar exhibited the highest sprouting percentage at 99.67% in both years, while King Roat (T_8) showed the minimum at 97.83% pooled across years. Per cent sprouting of seedling is entirely dependent on rootstock characteristics, its viability, favourable environmental conditions, soil conditions and biotic or abiotic stresses [18]. Sprouting is influenced by temperature and low sub-zero temperatures on early dates of grafting, could have delayed the sprouting, while comparatively higher temperature and humidity on later dates may have helped in early sprouting [25]. In our findings, the variable sprouting may be due to the genetic variation among seedlings and temperature fluctuations after planting the seedlings. The mean sprouting percentage of 98.91% in 2019-20 and 98.97% in 2020-21 reflects nearly universal bud break across all cultivars, demonstrating optimal micro-environmental conditions and effective graft union formation.

Per cent graft success: A cursory glance at the data (Table I) indicates that Gale Gala (T_{10}) demonstrated exceptional compatibility with seedling rootstock, achieving 95.97% graft success in both years, representing the single best performing cultivar in the study. Conversely, Redlum Gala (T_9) recorded the lowest success at 91.90% pooled. Generally, a successful grafting includes the formation of necrotic layer, callus production, first cohesion of stock and scion by the callus junction, subsequent reduction or elimination of necrotic layer in callus, differentiation of some cells to the cambial cells, bridging of cambium tissues of stock and scion and finally formation and strong connection of vascular tissues [11], [27], [31]. In this study, it was determined that rootstocks and cultivars/genotypes had an important effect on the graft sprout ratio. The temperature immediately after grafting has a direct impact on its success and in order for the callus tissue to form the graft, the environmental conditions, particularly the temperature and humidity, must be ideal [3], [8], [14]. Such consistently high graft success rates (>91%) indicate successful vascular reconnection between scion and rootstock tissues, enabling rapid nutrient and water transport to the aerial portion of the graft. [28]. Our findings are in agreement with the results obtained by [5], who recorded maximum graft success (92.50 %) in Royal Delicious cultivar of apple at the nursery stage. [16] also obtained similar observations in per cent graft success rate of cultivars of Gala series in their experiment at the nursery stage.

Plant height (cm): A perusal of analyzed data presented in Table II indicates that among all evaluated genotypes, the Gala Group exhibited the most vigorous vegetative growth. Redlum Gala (T_9) recorded the maximum pooled plant height of 185.67 cm. Conversely, the Spur Group recorded the lowest plant height, confirming their genetic compactness. Schelet Spur (T_4) exhibited the minimum growth with a pooled height of 132.98 cm indicating distinct dwarf characteristics valued for high-density planting systems. Plant growth is the process by which a plant grows in size through cell division and enlargement, which includes the synthesis of new cellular material and the organisation of subcellular organelles. The height of the plant is greatly influenced by the rootstock and scion cultivar and is result of the genetically coded characteristics of the cultivars. Differences in graft shoot length were most likely due to genetic, ecological and cultivation practices, or could be due to genetic differences between the cultivar and rootstock, ecology and growing conditions [14]. Our findings agree with [16], who observed maximum plant height and vegetative growth, in the Gala series than other apple cultivars at nursery stage.

Stock Diameter (mm): A cursory glance of the data (Table II) revealed that among the cultivars, Chelan Spur (T_5) exhibited the highest pooled stock diameter (10.90 mm), followed by Schelet Spur (10.87 mm) and Scarlet Spur II (10.80 mm). The lowest stock diameter was recorded for King Roat (9.76 mm). Generally, size and diameter of the seedling used as rootstock is of pencil thickness (>7 mm). After successful grafting with the scion, the vigour and increase in growth of the stock completely depends upon the genetic characteristics of the rootstock, cultivar grafted on it and environmental conditions [7]. Our results are in agreement with the results obtained by [22] who conducted an experiment on response of different rootstock and scion combinations on the success of grafting in Apple, observed similar trends regarding spur cultivars showing higher stock diameter than other cultivars. [17] also recorded greater radial growth of the tongue grafted with apple cv. Redspur on seedling rootstock. [23] recorded stock diameter of Scarlet Gala in their experiment and results were in accordance to our recorded findings in Gala cultivars under nursery conditions.

Scion Diameter (mm): The data in Table II are clearly envisaging that the maximum scion diameter was recorded for Chelan Spur (T_5, 10.56 mm), followed by Schelet Spur (T_4, 10.47 mm) and Scarlet Spur II (T_3, 10.27 mm). The lowest scion diameter was observed in King Roat (T_8, 9.38 mm).

The higher scion diameters in the Spur Group indicate better resource allocation to the above-ground parts, which can translate into improved canopy development and fruiting potential. The stock or scion radial growth is dependent on the vegetative growth characteristics of scion cultivars. The differential growth varies differently for standard and spur type cultivars. The results of our findings are in agreements with the results recorded by [22], where similar results of spur varieties showing higher scion diameter than other varieties in the experiment were obtained, as due to compact height of spur cultivars, which resulted in significantly thick scion diameter than other standard apple cultivars.

Number of leaves/ plants: A cursory glance of the data (Table III) indicates that the maximum number of leaves/ plants was recorded for Royal Delicious (T_1, 45.00), followed by Jeromine (T_6, 43.17). The lowest number of leaves/ plants was observed in King Roat (T_8 ,36.67) followed by Schelet Spur (T_4, 38.17), demonstrating deliberate developmental constraints characteristic of dwarf-type cultivars bred for intensive management and enhanced reproductive efficiency through suppressed vegetative growth. The variation in number of leaves is mostly dependent on the plant height and number of nodes. Standard and spur type cultivars varies in their shoot growth and thus giving rise to variation in number of leaves. Our findings agree with [13], who recorded similar results in number of leaves per plant in Red Delicious cultivar of apple under nursery conditions which may be due to its vigorous nature. Higher number of leaves in Scarlet Spur II might be attributed to more condensed growth of the scion cultivar [13].

Leaf area (cm^2): A critical perusal of data in Table III indicated that among the different cultivars, the maximum leaf was recorded for Royal Delicious (34.48 cm^2), followed by Vance Delicious (32.79 cm^2) whereas, lowest leaf area was observed in Schelet Spur (26.45 cm^2), followed by Chelan Spur (26.84 cm^2). The higher leaf area in the Delicious Group indicates their potential for high photosynthetic activity and fruit production whereas, Spur type, having lower leaf area, reflects their compact growth habit and reduced vegetative competition. The size of the leaf is predominantly dependent on the genetic characteristics of the cultivar grafted on the rootstock and then followed by rootstock characteristics, environmental conditions and topography of the nursery. Individual leaf area is determined by leaf cell proliferation rates (affecting cell number) and cell expansion magnitude (affecting final cell size). Leaf area and other vegetative growth are also linked with the water supply restriction to the scion induced by anatomical characteristics of the rootstock [1], [23] recorded leaf area in Scarlet Gala ranging from 30.20 cm^2 to 32.77 cm^2, which is in close resemblance to our leaf area observations recorded in Gala cultivars under nursery conditions. [6] in their experiment recorded leaf area (29.30 cm^2) in Jeromine cultivar which is in accordance to our observations recorded for Jeromine on leaf area in the nursery.

Chlorophyll content (mg/g): Data presented in Table III highlight that among different cultivars, maximum chlorophyll content was observed in the Gala group, particularly in Gale Gala (2.65 mg/g), representing the highest photosynthetic pigment concentration among all evaluated cultivars, indicating superior light-harvesting capacity and maximal photosynthetic potential. The Spur group had the most consistent chlorophyll content, with values tightly clustered around 2.46 mg/g. This elevated chlorophyll level reflects the physiological adaptation of dwarf semi-spur types to accommodate growth constraints through enhanced photosynthetic efficiency per unit leaf area. The chlorophyll content may vary depending on the genetic makeup of plant and leaf area. The leaves of dwarfing apple trees have the highest photosynthetic productivity when compared to robust rootstocks [21], [32], [33].

Root Length (cm): The data recorded Table IV, clearly show that the maximum pooled root length was recorded in Gale Gala (T_{10}, 25.57 cm) and Schelet Spur (T_5, 21.11 cm) recorded the lowest. Longer root systems, as shown by T_{10} generally enhance soil exploration, water uptake and nutrient acquisition, which can support better vigour and stress tolerance in perennial fruit crops [30]. Conversely, cultivars like Schelet Spur with shorter roots may be more vulnerable under limiting soil conditions and may require better irrigation and nutrient management to perform optimally. The stability of treatment effects across years suggests that these root traits are genetically controlled and can be used as a selection criterion in rootstock-scion evaluation and genotypic improvement programmes [15]. It is generally mistaken that the vigour and growth of root is solely dependent on the type of rootstock used, but the type of cultivar grafted on the stock also plays a crucial role in determination of root vigour and growth as after successful grafting and healing genetically coded characteristics of the cultivar or variety exhibits its impact on role of xylem and phloem, nutritional requirement in the plant. [23] recorded maximum root length (25.78 cm) in Scarlet Gala, which were closely similar to our findings, where more root length was recorded in Gala cultivars under nursery conditions. [28] recorded maximum root length (20.10 cm) in Gala Mast grafted on crab apple as crab apple, rootstock penetrates deeper and spread horizontally than M26 due to the presence of a taproot system.

Root weight (g): A cursory glance of the data (Table IV) revealed that root weight exhibited significant genotypic variation among the 11 apple cultivars, with Jeromine (T_6) producing the heaviest root systems (57.00 g) and Vance Delicious (T_2) the lightest (35.00 g). Root weight is a crucial indicator of root system development and the plant's ability to absorb water and nutrients, directly influencing tree vigour and productivity. The results show that Jeromine exhibited the highest root weight, suggesting a robust root system capable of efficient resource uptake. Genetic differences among scion types distinctly influence rootstock growth and vigour, affecting traits such as root length, diameter, and overall size. The fresh root weight reflects the scion's key role in root development, likely mediated by factors like leaf number, leaf area, and chlorophyll content, which increase photoassimilate production and allocation to the roots [9]. Cultivars like Jeromine, Gale Gala, and Red Velox, with greater root biomass, benefit from improved water and nutrient uptake, stronger anchorage, and greater carbohydrate reserves. Generally, larger root systems in rootstock-scion combinations support better drought tolerance, nutrient efficiency, and resilience under challenging soil conditions [37].

Per cent survival: A critical perusal of data in Table V indicated that Gale Gala (T_{10}) demonstrated the highest survival at 94.50%, while King Roat (T_8) showed the lowest at 87.83%.

The difference in survival rate of the different cultivars might be attributed due to factors like proper graft union, sprouting of seedling, movement of sap, healing and failure of graft union which results in drying and ultimately death to the grafted plant. Grafting failure due to incompatibility or improper cuts on stock and scion at graft union may be another factor accounting for survival of grafts [19], [29]. Also, due to presence of unfavourable environmental conditions during grafting, results in weak or dead plants. The excellent survival rates observed in Gale Gala and Gala Mast suggest rapid and complete graft union formation, ensuring unimpeded water and nutrient translocation between stock and scion. It has been emphasised that graft incompatibility is a complex event that can be caused by physiological, anatomical, or biochemical factors and that the survival ratio is lower in scion/stock combinations with high graft incompatibility [10], [26].

Per cent healthy plants: The data in Table V are clearly indicate that among the 11 apple cultivars, with Gale Gala (T_{10}) exhibits the highest proportion of healthy plants (88.83%). Superior plant health in Gale Gala and other Gala group cultivars indicates stronger constitutive and inducible disease resistance mechanisms, enhanced vigour, and better environmental stress tolerance during nursery production. Conversely, King Roat (T_8), with only 75.17 per cent healthy plants, demonstrates heightened susceptibility to nursery pathogens and stress conditions [2]. There was a noticeable interaction between cultivar and year, as some cultivars performed better in one year than the other. This interaction can be attributed to differences in environmental conditions, especially temperature and rainfall. The year-to-year variation, driven by weather fluctuations, highlights the importance of considering local climate conditions when choosing cultivars for apple nursery management. C × Y interaction was evident, with some cultivars benefiting from higher spring temperatures and others suffering from increased humidity and rainfall in the monsoon season. High humidity and rainfall in July-August of both years may have increased disease pressure, affecting cultivars differently based on their tolerance. The plants survived and selected after discarding diseased plants (Crown gall & Hairy root) are termed as the healthy plants, which are classified on the basis of height, thickness of scion and sound root system. Both Crown gall and Hairy root are soil-borne diseases, so the presence of these bacteria in the soil, previous year's crop may be a cause of their infestation because the bacterium survives in the soil as discussed earlier. Furthermore, the infestation rate is also entirely natural, as none of the cultivars are more or less susceptible or resistant to crown gall and hairy root and the percentage of infestation is most probably dependent on the grafting wounds, frost injury cracks and the presence of bacteria in the soil of that particular cultivar bed.

Per cent saleable plants: A perusal of analyzed data presented in Table V indicates that among the 11 apple cultivars, with Gale Gala (T_{10}) achieving the highest proportion (78.67%) and King Roat (T_8) the lowest (65.50%) The plants with a height of more than 90 cm, having pencil thickness diameter or more, bearing well developed roots and free from insect pests and disease infestations were considered to be saleable plants. The undersized healthy plants were not categorised as saleable plants as they don't met the conditions required for saleable plants. The cultivars of Gala series had induced larger vegetative growth variables than others which aid them to exhibit high healthy and saleable per cent than other cultivars. [16] had already discussed maximum vegetative growth in Gala series cultivars that had met all the standards for saleable plants, resulting in highest number of saleable plants than other apple cultivars at the nursery stage in their performed experiment. The significant year interaction underscores the importance of considering annual weather patterns when selecting cultivars. Warmer, drier springs favoured some Spur Group cultivars, while others, like Jeromine, may be more sensitive to climatic stress. These findings align with studies showing that apple nursery performance is influenced by temperature and rainfall patterns, especially during critical growth stages.

Principal Component Analysis of different nursery parameters: The Principal Component Analysis (PCA) was employed to reduce the dimensionality of the eleven morphological and physiological traits, revealing that the first two principal components explain a cumulative 62.7% of the total variance (PC1: 41.82%, PC2: 20.88%). This high proportion of explained variance indicates that the selected parameters effectively capture the major phenotypic diversity among the apple cultivars. PC1 (41.82% variance) represents a 'vegetative vigour' axis, with strong positive loadings for leaf area, leaf number, plant height, and root characteristics, indicating cultivars emphasising rapid growth and photosynthetic capacity. PC2 (20.88% variance) represents a 'structural development' axis, contrasting leafy growth (positive) with woody stem development and horticultural output metrics (negative). The biplot demonstrated two contrasting cultivar strategies. Cultivars positioned on the right (positive PC1) prioritise rapid vegetative growth and large photosynthetic surfaces, while the isolated left-positioned cultivar emphasises structural development with superior graft success, survival percentage, and saleable plant output.

Strong positive correlations among graft success, survival percentage, and saleable plants percentage indicate these traits are physiologically linked, simplifying selection criteria for nursery breeding programs. The inverse relationship between vigour traits (PC1 positive) and grafting quality (PC1 negative) reflects a physiological trade-off in resource allocation between shoot extension and woody tissue development. [4], [20], [34] The 62.70% cumulative variance explained by PC1 and PC2 provides robust cultivar differentiation. The analysis reveals that cultivar performance cannot be adequately assessed through single-trait evaluation; multivariate approaches identify complex relationships essential for informed breeding decisions. Maintaining diverse cultivars in nursery operations optimises flexibility for different market demands and management scenarios.

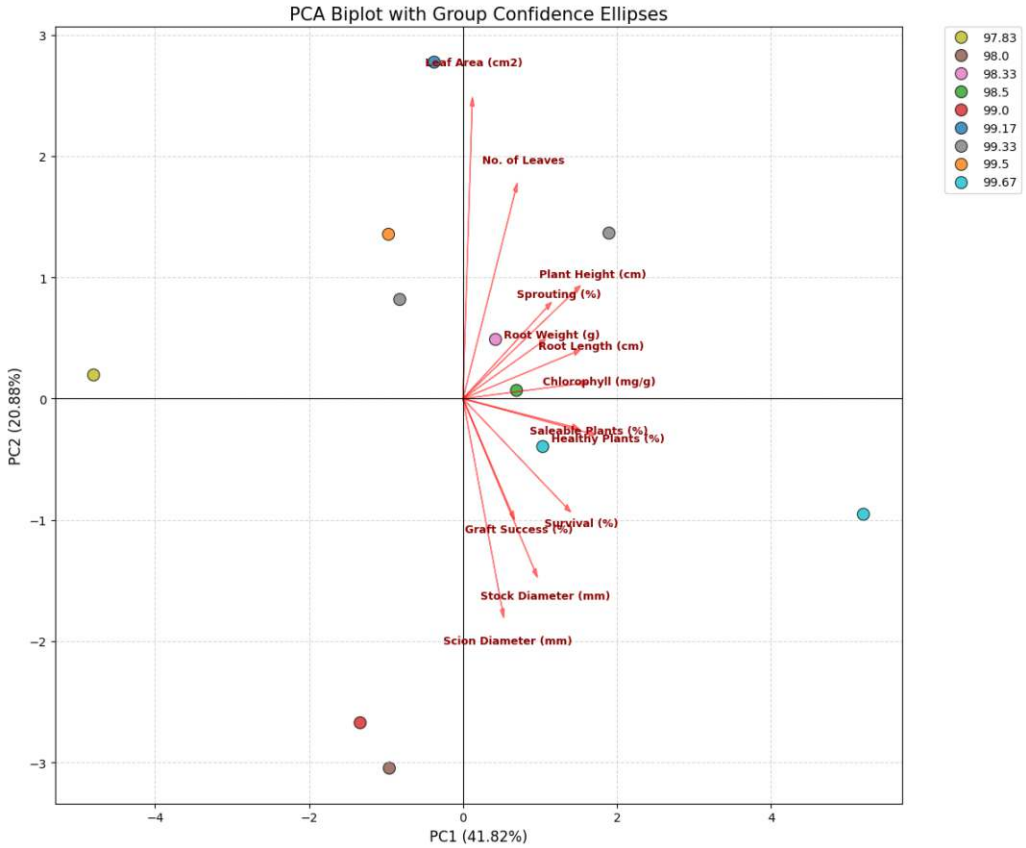


Fig. 4. PCA Biplot analysis for different nursery parameters.

Table I. Propagation efficiency of different apple cultivars grafted on seedling rootstock

Cultivars / Parameters			Per cent sprouting			Per cent graft Success		
			2019-20	2020-21	Pooled*	2019-20	2020-21	Pooled*
Delicious Group	T_1	Royal Delicious	99.33	99.00	99.17 (9.96)	92.55	92.64	92.60 (9.62)
	T_2	Vance Delicious	99.33	99.67	99.50 (9.98)	93.58	94.01	93.80 (9.68)
Spur Group	T_3	Scarlet Spur II	98.33	98.67	98.50 (9.92)	93.55	93.49	93.52 (9.67)
	T_4	Schelet Spur	99.00	99.00	99.00 (9.95)	93.22	93.26	93.24 (9.66)
	T_5	Chelan Spur	98.00	98.00	98.00 (9.90)	94.15	93.51	93.83 (9.69)
Semi-Spur Group	T_6	Jeromine	98.33	98.33	98.33 (9.92)	93.52	93.31	93.41 (9.67)
	T_7	Red Velox	99.33	99.33	99.33 (9.97)	94.26	94.26	94.26 (9.71)
	T_8	King Roat	97.67	98.00	97.83 (9.89)	93.81	93.71	93.76 (9.68)
Gala Group	T_9	Redlum Gala	99.33	99.33	99.33 (9.97)	91.90	91.90	91.90 (9.59)
	T_{10}	Gale Gala	99.67	99.67	99.67 (9.98)	95.98	95.97	95.97 (9.80)
	T_{11}	Gala Mast	99.67	99.67	99.67 (9.98)	94.93	94.08	94.51 (9.72)
Mean			98.91	98.97		93.77	93.65	
CD_{50}			C		0.82			1.37
			Y		NS			NS
			C×Y		NS			NS

**Figure in the parenthesis represents square root transformation*

Table II. Shoot growth parameters of different apple cultivars grafted on seedling rootstock

Cultivars / Parameters			Height (cm)			Stock diameter (mm)			Scion diameter (mm)		
			2019-20	2020-21	Pooled	2019-20	2020-21	Pooled	2019-20	2020-21	Pooled
Delicious Group	**T_1**	Royal Delicious	153.33	160.35	156.84	10.15	10.30	10.23	9.55	9.75	9.65
	T_2	Vance Delicious	147.00	151.20	149.10	9.93	10.12	10.02	9.30	9.51	9.40
Spur Group	**T_3**	Scarlet Spur II	158.00	160.03	159.02	10.70	10.90	10.80	10.21	10.34	10.27
	T_4	Schelet Spur	130.50	135.47	132.98	10.77	10.91	10.87	10.37	10.56	10.47
	T_5	Chelan Spur	144.33	150.57	147.45	10.85	10.95	10.90	10.45	10.66	10.56
Semi-Spur Group	**T_6**	Jeromine	169.33	173.50	171.42	10.75	10.92	10.83	10.31	10.53	10.42
	T_7	Red Velox	151.67	157.40	154.53	9.90	10.11	10.01	9.61	9.76	9.69
	T_8	King Roat	134.83	139.63	137.23	9.67	9.85	9.76	9.30	9.46	9.38
Gala Group	**T_9**	Redlum Gala	182.67	188.67	185.67	10.55	10.77	10.66	9.89	9.98	9.94
	T_{10}	Gale Gala	177.83	181.47	179.65	10.54	10.71	10.63	9.92	10.01	9.97
	T_{11}	Gala Mast	157.17	162.17	159.67	10.62	10.87	10.75	9.98	10.11	10.05
Mean			155.15	160.04		10.40	10.58		9.90	10.06	
CD_{50}			C		5.76			0.11			0.10
			Y		NS			NS			NS
			C×Y		NS			NS			NS

Table III. Leaf parameters of different apple cultivars grafted on seedling rootstock

Cultivars / Parameters			No. of leaves /plants			Leaf area (cm^2)			Chlorophyll content (mg/g)		
			2019-20	2020-21	Pooled	2019-20	2020-21	Pooled	2019-20	2020-21	Pooled
Delicious Group	T_1	Royal Delicious	44.33	45.67	45.00	34.20	34.77	34.48	2.47	2.49	2.48
	T_2	Vance Delicious	39.33	41.33	40.33	32.56	33.03	32.79	2.40	2.43	2.41
Spur Group	T_3	Scarlet Spur II	41.33	41.00	41.17	31.39	32.06	31.72	2.52	2.51	2.52
	T_4	Schelet Spur	37.67	38.67	38.17	26.19	26.70	26.45	2.39	2.42	2.40
	T_5	Chelan Spur	38.00	37.33	37.67	26.44	27.23	26.84	2.44	2.48	2.46
Semi-Spur Group	T_6	Jeromine	42.33	44.00	43.17	31.27	31.94	31.60	2.34	2.38	2.36
	T_7	Red Velox	39.00	40.67	39.83	30.76	31.44	31.10	2.43	2.41	2.42
	T_8	King Roat	36.33	37.00	36.67	29.71	30.38	30.05	2.25	2.28	2.27
Gala Group	T_9	Redlum Gala	40.33	40.67	40.50	31.25	31.91	31.58	2.62	2.65	2.63
	T_{10}	Gale Gala	39.67	40.33	40.00	28.80	29.47	29.13	2.64	2.67	2.65
	T_{11}	Gala Mast	40.00	40.67	40.33	31.05	31.52	31.29	2.45	2.42	2.43
Mean			39.85	40.67		30.33	30.95		2.45	2.27	
CD_{50}			C		2.66			1.11			0.04
			Y		NS			NS			NS
			C×Y		NS			NS			NS

Table IV. Root growth parameters of different apple cultivars grafted on seedling rootstock

Cultivars / Parameters			Root length (cm)			Root weight (g)		
			2019-20	2020-21	Pooled	2019-20	2020-21	Pooled
Delicious Group	T_1	Royal Delicious	22.00	22.83	22.42	37.33	39.00	38.17
	T_2	Vance Delicious	21.33	21.83	21.58	34.33	35.67	35.00
Spur Group	T_3	Scarlet Spur II	23.11	23.57	23.34	49.17	50.17	49.67
	T_4	Schelet Spur	20.50	21.73	21.11	35.00	36.33	35.67
	T_5	Chelan Spur	20.83	21.88	21.36	37.33	38.67	38.00
Semi-Spur Group	T_6	Jeromine	23.67	24.13	23.90	56.17	57.83	57.00
	T_7	Red Velox	21.00	21.47	21.23	49.83	51.35	50.59
	T_8	King Roat	21.50	21.50	21.50	38.67	40.17	39.42
Gala Group	T_9	Redlum Gala	23.00	23.69	23.35	49.17	50.17	49.67
	T_{10}	Gale Gala	25.17	25.98	25.57	51.33	52.62	51.98
	T_{11}	Gala Mast	21.67	22.29	21.98	42.67	43.50	43.08
Mean			22.16	22.81		43.73	45.04	
CD_{50}			C		1.63			3.10
			Y		NS			NS
			C×Y		NS			NS

Table V. Quality parameters of different apple cultivars grafted on seedling rootstock

Cultivars / Parameters			Per cent survival			Per cent healthy plants			Per cent saleable plants		
			2019-20	2020-21	Pooled*	2019-20	2020-21	Pooled*	2019-20	2020-21	Pooled+
Delicious Group	T_1	Royal Delicious	89.00	89.33	89.00 (9.43)	81.33	79.33	80.33 (8.96)	74.67	73.00	73.83 (60.68)
	T_2	Vance Delicious	90.00	90.33	90.17 (9.50)	82.67	81.33	82.00 (9.06)	74.00	72.67	73.33 (60.43)
Spur Group	T_3	Scarlet Spur II	89.00	89.33	89.17 (9.44)	79.67	80.33	80.00 (8.84)	73.00	75.33	76.00 (62.18)
	T_4	Schelet Spur	89.33	89.67	89.50 (9.49)	81.33	80.00	80.67 (8.98)	69.33	74.00	74.83 (61.47)
	T_5	Chelan Spur	90.67	90.67	90.67 (9.52)	81.67	80.33	81.00 (9.00)	70.67	71.33	72.17 (59.75)
Semi-Spur Group	T_6	Jeromine	89.67	90.00	89.83 (9.48)	81.00	80.00	80.50 (8.97)	76.67	68.00	68.67 (57.58)
	T_7	Red Velox	89.33	89.67	89.50 (9.49)	81.00	82.33	81.67 (9.04)	75.67	69.67	70.17 (58.86)
	T_8	King Roat	88.00	87.67	87.83 (9.37)	76.00	74.33	75.17 (8.67)	66.33	64.67	65.50 (55.38)
Gala Group	T_9	Redlum Gala	88.67	88.67	88.67 (9.42)	82.33	83.33	82.83 (9.10)	76.00	77.67	76.83 (62.82)
	T_{10}	Gale Gala	94.33	94.67	94.50 (9.72)	88.33	89.33	88.83 (9.42)	78.00	79.33	78.67 (64.25)
	T_{11}	Gala Mast	91.67	92.00	91.83 (9.58)	83.67	82.33	83.00 (9.11)	74.00	75.00	74.50 (61.14)
Mean			89.97	90.18		81.72	81.18		73.48	72.79	
CD_{50}			C		1.22			1.98			2.09
			Y		NS			0.52			0.39
			C×Y		NS			1.74			1.28

Figure in the parenthesis represents square root transformation
+*Figure in the parenthesis represents angular transformation*

CONCLUSION

Gale Gala when grafted on seedling rootstock emerged as the superior cultivar, demonstrating exceptional propagation efficiency (95.97% graft success), vigorous growth (179.65 cm height), highest photosynthetic pigment concentration (2.65 mg/g chlorophyll content), robust root development (25.57 cm length, 51.98 g weight), and outstanding quality metrics (94.50% survival, 88.83% healthy, 78.67% saleable plants) under nursery conditions. Conversely, King Roat underperformed across all parameters. These genotypic differences reflect inherent variations in scion-rootstock compatibility, vigour expression, and disease resistance, confirming cultivar selection as a critical strategy for optimising nursery productivity and orchard success under temperate conditions.

Future Scope

The conducted investigation provided a foundational framework for strengthening apple orchard establishment in hill ecosystems. However, several researchable dimensions remain open for further refinement and wider application of the findings. Integrating physiological and biochemical parameters, such as carbohydrate reserves, root hydraulic conductivity, graft union anatomy, and hormonal balance would help in better understanding and explaining the differences in graft success, seedling vigour, and early growth behaviour. These parameters would strengthen the biological basis for selecting superior nursery combinations beyond morphological observations alone. Further researches may explore comparative evaluation of seedling rootstock with clonal and semi-clonal rootstocks under identical nursery conditions. This would provide a clearer understanding of the relative advantages of seedling rootstocks in terms of adaptability, cost, and long-term orchard performance, especially in marginal hill environments where uniformity is often compromised by abiotic stresses. Additionally, evaluating the response of promising cultivar-rootstock combinations to biotic stresses and abiotic stresses at the nursery stage may help in producing resilient planting material suited to climate variability.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

1. Atkinson, C, J., Else, M, A., Taylor, L., & Dover, C, J. (2003). Root and stem hydraulic conductivity as determinants of growth potential in grafted trees of apple (*Malus pumila* Mill.). *Journal of Experimental Botany,* 54, 1221-29.

2. Bálint, J., Thiesz, R., Nyárádi, I., Szabó, K. (2013). Field evaluation of traditional Apple cultivars to induced diseases and pests. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 41(1), 238-243.

3. Baron, D., Amaro, A, C, E., Pina, A., & Ferreira, G. (2019). An overview of grafting re-establishment in woody fruit species. *Scientia Horticulturae,* 243, 84-91.

4. Biasuz, E, C., & Kalcsits, L, A. (2022). Apple rootstocks affect functional leaf traits with consequential effects on carbon isotope composition and vegetative vigour. *AoB PLANTS*, 14, 1-11.

5. Devkota, T, R., Gahatraj, S., Shrestha, B., & Karki, Y, K. (2019). Effect of grafting dates and wrapping materials on grafting success of apple (*Malus × domestica* cv. Royal Delicious) in Jumla, Nepal. *Journal of Agricultural Science and Practice,* 5, 55-59.

6. Dhiman, N., Chandel, J, S., Verma, P. (2018). Effect of planting density on growth, yield and fruit quality of apple cv. Jeromine. *Journal of Hill Agriculture,* 9, 289-291.

7. Dolgun, O., Yildirim, A., Polat, M., Yildirim, F., & Askin, A. (2009). Apple graft formation in relation to growth rate features of rootstocks. *African Journal of Agricultural Research,* 4:530-34.

8. Dolkar, T., Mansoor, A., Agleema, B., Divya, S., Lobzang, S., & Stanzin, K. (2018). Mitigation of temperate fruit crop problems through use of rootstock. *International Journal of Chemical Studies,* 6, 880-887.

9. Eissenstat, D, M., Wells, C, E, & Wang, L. (2001). Root efficiency and mineral nutrition in Apple. *Acta Horticulturae*. 564, 165-183. https://doi.org/10.17660/ActaHortic.2001.564.19.

10. Errea, P. (1998). Implications of phenolic compounds in graft incompatibility in fruit tree species. *Scientia Horticulturae,* 74, 195-205.

11. Estrada-Luna, A, A., Lopez-Peralta, C., & Cardenas-Soriano, E. (2002). In vitro micrografting and the histology of graft union formation of selected species of prickly pear cactus (*Opuntia* spp.). *Scientia Horticulturae,* 92, 317-327.

12. Fazio, G., & Robinson, T. (2008). Modification of nursery tree architecture with apple rootstocks: A breeding perspective. *New York Fruit Quarterly,* 16, 13-16.

13. Gangwar, M, P., Rai, R., Karnwal, M, K., Singh, Y, P., & Kumar, C. (2010). Evaluation of apple cultivars introduced from New Zealand at nursery stage. *Progressive Horticulture,* 42, 235-236.

14. Hartmann, H, T., Kester, D, E., Davies, F, T., & Geneve, R, L. (2011). *Plant propagation: Principles and practices.* 8th ed. Regents/Prentice Hall International Edition. Englewood Cliffs, New Jersey. 928p.

15. Jung, Y., Park, K., Jensen, K, H., Kim, W., Kim, H, Y. (2019) A design principle of root length distribution of plants. *Journal of The Royal Society Interface,* 16 (161), 20190556. http://dx.doi.org/10.1098/rsif.2019.0556.

16. Karamursel, F, O., & Kalyoncu, H, I. (2011). Nursery growing of some apple varieties using different grafting methods in greenhouse and orchard. *African Journal of Biotechnology,* 10, 19375-19384.

17. Kumar, R., & Ananda, S, A. (2004). Effect of methods and height of grafting on the growth of grafted plants and the feather in spur types cultivars of apple in nursery. *Progressive Horticulture* 36, 230-33.

18. Kviklys, D., Lanauskas, J., Sakalauskaite, J., Kvikliene, N., & Uselis N. (2008). Soil exhaustion and rootstock effect on the growth of apple planting material. *Agronomy Research,* 6, 511-516.

19. Lawrence, B, T., Fazio, G., Nieto, L, G., & Robinson, T, L. (2025). Rootstock effect on horticultural performance and fruit quality is not uniform across five commercial apple cultivars in western New York. *Frontiers in Plant Science,* Volume 16. https://doi.org/10.3389/fpls.2025.1552625.

20. Li, Q., Gao, Y., Wang, K., Feng, J., Sun, S., Lu, X., Liu, Z., Zhao, D., Li., & Wang, D. (2023). Transcriptome analysis of the effects of grafting interstocks on apple rootstocks and scions. *International Journal of Molecular Sciences,* 24, 807. https://doi.org/10.3390/ijms24010807.

21. Maidebura, V, I., Kumpan, E, D., & Aleksandryvk, M, Y. (1978). The assimilating area of the apple cultivar Reinette de champagne in relation to the rootstock. *Nauchnye Trudy Ukrain S-Kh Akad,* 220, 39-41.

22. Malasi, P., Thakur, N., & Manglore, N, C. (2017). Response of different rootstock and scion combinations on the success of grafting in apple *(Malus × domestica). International Journal of Current Microbiology and Applied Sciences,* 6, 1193-1200.

23. Negi, N, D., & Upadhayay, S, K. (2017). Standardization of summer grafting dates in apple under polyhouse conditions in mid-hill areas of Himachal Pradesh. *Himachal Journal of Agricultural Research,* 43, 48-53.

24. Panse, V, G., & Sukhatme, P, V. (1954). *Statistical methods for agricultural workers*. Indian Council of Agricultural Research, New Delhi. 361p.

25. Pathak, R, K. (1991). Propagation of Fruit Plants. Indian Council of Agriculture Research, New Delhi. 22p.

26. Pina, A., & Errea, P. (2005). A review of new advances in mechanism of graft compatibility-incompatibility. *Scientia Horticulturae,* 106, 1-11.

27. Pina, A., & Errea, P. (2008). Influence of graft incompatibility on gene expression and enzymatic activity of UDP-glucose pyrophosphorylase. *Plant Sciences*, 174, 502-09.

28. Rabi, F., Rab, A., Bostan, N., Sajid, M., & Rahman, K. (2016). Growth behaviour of apple cultivars on different apple rootstock. *Pure and Applied Biology,* 5(2), 339-344.

29. Rasool, A., Mansoor S, Bhat, K, M., Hassan, G, I., Baba, T, R., Alyemeni M, N., Alsahli A, A., El-Serehy H, A., Paray B, A., & Ahmad P. (2020). Mechanisms underlying graft union formation and rootstock scion interaction in horticultural plants. *Frontiers in Plant Science.* Volume 11. https://doi.org/10.3389/fpls.2020.590847.

30. Schlüter, S., Blaser S, R, G, A., Weber, M., Schmidt, V., & Vetterlein D. (2018). Quantification of Root Growth Patterns from the Soil Perspective via Root Distance Models. *Frontiers in Plant Science*, 9, 1084. doi: 10.3389/fpls.2018.01084.

31. Sitarek, M. (2006). Incompatibility problems in sweet cherry trees on dwarfing rootstocks. *Latvian Journal of Agronomy,* 9, 140-145.

32. Titova, N, V., & Shishkanu, G, V. (1976). Photosynthesis and pigment content in apple trees on different rootstocks. *Referativnyi Zhurnal,* 9, 825.

33. Trunov, L, A., & Muromtsev, L, A. (1980). Effect of rootstock on the activity of the root system and on photosynthesis in apple trees. *Sadovodstvo Uinograelarstuo i Vinodelie Moldavil,* 9, 28-29.

34. Tworkoski, T., & Miller, S. (2007). Rootstock effect on growth of apple scions with different growth habits. *Scientia Horticulturae,* 111, 335-343.

35. Wani, F, A., and Songara, M. (2018). Status and position of apple crop in area, production and productivity in Himachal Pradesh. *International Journal of Multidisciplinary Research and Development* 5:106-11.

36. Wertheim, S, J. (1998). Rootstock guide: Apple, pear, cherry, european plum. Fruit Research Station, Wilhelminadorp, The Netherlands. 75p.

37. Xu, H., & Ediger, D. (2021). Rootstocks with Different vigor influenced scion-water relations and stress responses in Ambrosia™ apple trees (*Malus Domestica* var. Ambrosia). *Plants (Basel, Switzerland)*, 10(4), 614. https://doi.org/10.3390/plants10040614.