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Apple Rootstocks and their Role in Orchard Performance: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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Abstract

Apple rootstocks play a crucial role in determining tree vigor, productivity, fruit quality, and adaptability to diverse environmental conditions in modern orchard systems. The development and selection of appropriate rootstocks have become increasingly important for improving orchard efficiency, particularly in high-density

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planting systems. This review synthesizes available literature on major apple rootstock groups, including Malling (M), Malling-Merton (MM), Geneva (G), and Budagovsky (B) rootstocks. The review highlights their classification, physiological characteristics, effects on tree growth and yield efficiency, and their role in improving resistance to diseases and tolerance to abiotic stresses such as drought, cold, and salinity. In addition, rootstock–scion interactions and their implications for orchard management and productivity are discussed. Recent advances in rootstock breeding, particularly the development of Geneva rootstocks for improved disease resistance and stress tolerance, are also summarized. The review provides insights into selecting suitable rootstocks for sustainable apple production and identifies future research directions for improving orchard performance under changing climatic conditions.

Keywords: Apple; rootstock; disease resistance; stress; production.

1. Introduction

Apple (*Malus domestica* Borkh.) is among the most extensively cultivated temperate fruit crops globally and holds a pivotal position in modern horticulture. The success of commercial apple production is largely contingent upon the selection of suitable rootstocks, as these significantly influence tree vigour, yield efficiency, fruit quality, and adaptability to diverse environmental conditions. At present, the apple industry is widely recognised as a promising sector for enhancing agricultural productivity, improving household nutritional security, and generating income through diversification, employment opportunities, value addition, and export potential.

Despite substantial progress in this sector, several constraints persist. In addition to emerging challenges, low productivity per unit area remains a major concern, further exacerbated by the adverse impacts of climate change. Rootstocks play a crucial role in apple production systems by influencing canopy architecture, nutrient uptake, flowering behaviour, yield, and fruit quality (Rom *et al*., 1987). Furthermore, they contribute to the mitigation of both biotic and abiotic stresses, including soil-borne pathogens, thermal stress, salinity, and nutrient imbalances (Reddy *et al*., 2003).

Owing to increasing market demand and limited availability of arable land, apple cultivation is often undertaken under suboptimal environmental conditions such as drought, flooding, salinity, and soil contamination. The use of appropriate rootstocks offers a viable strategy to alleviate such constraints by enhancing the resilience of the scion to adverse environmental factors (Higgs *et al*., 1991). Rootstocks are fundamental determinants of orchard efficiency, as they regulate water and mineral uptake, provide anchorage, and influence overall tree size (Ferree & Warrington, 2003).

In addition to their primary functions, rootstocks may also be utilised as interstems—short stem segments inserted between the rootstock and scion during propagation—resulting in "three-piece" trees (Cummins & Aldwinckle, 1983). Interstems can help overcome graft incompatibility and reduce excessive vigour in otherwise desirable rootstocks (Rom & Carlson, 1987). Moreover, certain rootstocks confer tolerance to unfavourable soil moisture conditions, whether excessively wet or dry.

Extensive research across different regions has highlighted the importance of rootstock selection in relation to vigour control, nutrient acquisition, salinity tolerance, moisture stress, and yield efficiency (Ferree & Warrington, 2003). However, many rootstocks with significant commercial potential remain underutilised in India. Therefore, the identification and evaluation of rootstocks with optimal combinations of desirable traits, tailored to specific environmental conditions, is essential. Notably, a rootstock considered ideal for a particular cultivar or agro-climatic condition may not perform similarly under different circumstances (Webster & Wertheim, 2003).

In this context, there is a need to synthesise key characteristics of major rootstock groups, including Geneva, Malling (M), and Malling-Merton (MM) series, particularly with respect to horticultural performance traits such as dwarfing capacity and yield efficiency, as well as resistance to diseases such as root rot, crown rot, and fire blight. Such information is critical for informed rootstock selection and for guiding future research efforts.

Modern apple orchards increasingly rely on dwarfing rootstocks, which enable high-density planting systems, early bearing, and enhanced productivity, thereby improving economic returns (Afonso *et al*., 2018). Rootstocks also influence important agronomic traits such as alternate bearing (Kviklys *et al*., 2016), resistance to pests and diseases (Beers *et al*., 2007), drought tolerance (Tworkoski & Fazio, 2016), phenological development, and fruit quality attributes, including sensory characteristics and physicochemical composition (Kviklys *et al*., 2015; Harrison *et al*., 2016).

Furthermore, rootstocks can affect the biosynthesis of aroma compounds in apples through their influence on carbohydrate and fatty acid metabolism pathways. Consequently, the strategic selection of rootstocks may be employed to enhance specific fruit quality traits, including aroma profiles (Gur *et al*., 2019).

This review, therefore, provides a comprehensive synthesis of major apple rootstock groups, their defining characteristics, and their influence on orchard performance, with particular emphasis on recent research developments and their implications for sustainable and efficient apple production systems.

Historical background of apple rootstocks: The cultivation of apples on dwarfing rootstocks can be traced back to at least the third century BCE in regions such as Persia and Asia Minor. Historical records suggest that Alexander the Great is believed to have transported a dwarf apple tree from Persia to the Lyceum, a renowned centre of learning founded by Aristotle. Theophrastus, a distinguished pupil of Aristotle and later director of the Lyceum, documented that dwarf apple trees had long been cultivated in Persia and Asia Minor. The Persian term *pardis*, meaning “heaven,” reflects the cultural and symbolic significance attributed to apples, which were often regarded as fruits of paradise. In both Persian and its Sanskrit equivalent *paradeca*, the term also denotes an enclosed orchard or garden.

The *pardis* apple type was characterised as a dwarfing, low-growing, and self-rooting form. The prevalence of dwarfing plants, as well as dwarf animals such as horses, in ancient Persia is evidenced in the iconography of Persepolis and in monuments associated with successive Persian dynasties, including the Achaemenian, Sassanian, Parthian, and Safavid periods. Linguistically, *pardis* evolved into the English word “paradise,” underscoring its enduring cultural legacy. By the mid-fifteenth century, the utilisation of dwarfing apple rootstocks for the training and management of fruit trees in gardens had become increasingly widespread in Europe. Two principal categories of rootstocks were recognised: the highly dwarfing French Paradise and the comparatively more vigorous Doucin, also referred to as English Paradise.

A significant advancement in the scientific classification and improvement of apple rootstocks occurred in the early twentieth century. In 1912, systematic efforts were initiated at the East Malling Research Station to collect Paradise and Doucin rootstocks from diverse geographical regions. Between 1912 and 1918, these materials were standardised and classified into the clonal Malling (M) series. Subsequently, in 1920, collaborative breeding programmes between East Malling and Merton research stations led to the development of the Malling-Merton (MM) rootstocks through hybridisation of the ‘Northern Spy’ cultivar with selected Malling types, thereby enhancing resistance to pests and adaptability.

Dwarfing rootstocks were introduced into the United States from Europe during the early nineteenth century, where their adoption exhibited cyclical patterns influenced by shifting horticultural and economic considerations (Tukey, 1964). In the early 1880s, their use was largely confined to ornamental horticulture and domestic gardens. Although interest expanded between 1835 and 1860, it declined in the subsequent decades (1860–1890), primarily due to overproduction and the resulting depression in fruit prices.

Renewed interest emerged around 1890, largely driven by the need to manage infestations of San Jose scale, as smaller trees were more amenable to fumigation using hydrogen cyanide gas. However, this resurgence was short-lived. The introduction of alternative pest control measures, notably lime sulphur and oil sprays between 1907 and 1910, significantly reduced reliance on dwarfing systems. Consequently, critical assessments such as those by Hall (1915), drawing upon the work of U.P. Hedrick, concluded that dwarf apple trees lacked commercial viability. By the 1920s, the use of dwarfing apple rootstocks had largely fallen into disrepute within commercial orcharding systems.

Malling rootstocks were first tested in New York, Pennsylvania, and Massachusetts in 1920. Later introductions included the Oregon Apple Rootstock (OAR1) in 1943, and the Cornell-Geneva (CG) series in 1953, developed from open-pollinated crosses of dwarfing M.8 with M.1–M.16 of the Malling series in Geneva, New York. Other rootstock series include the Polish (P) series in 1954, the Ottawa (O) series in 1961, the Budagovsky (B or Bud.) series in 1976, and the Michigan Apple Clonal (MAC) series in 1980.

Subsequent research refuted Hall's 1915 conclusion, and today, the majority of apple orchards in the United States and worldwide are planted on clonal dwarfing rootstocks (Kelsall, 1946; Regional Rootstock Research Project NC-140, 1991; Norton, 1970).

This historical progression illustrates the global development of dwarfing rootstocks, their cultural significance, and their eventual adoption in modern apple production systems.

2. Classification of Rootstocks

There are five types of rootstocks in apple. These include Budagovsky(Bud or B), Cornell/ Geneva(CGorG), Malling (M) and Malling Merton(MM), Michigan Apple Rootstock Clones (MARK) and EastMalling/ Ashton Long(EMLA) and out of which the major series are Budagovsky(Bud or B), Cornell/ Geneva(CGorG), Malling (M) and Malling Merton(MM), which are discussed and reviewed in this paper.

a. M-Series:

The "M" series of apple rootstocks, developed at the East Malling Research Station in England in the early 20th century, have been foundational in modern apple production (Cummins &Aldwinckle, 1983). The rootstocks in this series were created to address the varying growth and soil conditions in apple orchards while also providing growers with options for controlling tree size, vigor, and yield. Each M-series rootstock is denoted by a number that signifies its level of vigor and other characteristics. For instance, M.9 is a dwarfing rootstock that encourages early fruit production and is widely used in high-density orchards, while M.7 is semi-dwarfing and more vigorous, making it suitable for less intensively managed systems (Fazio *et al*., 2015). However, traditional M-series rootstocks like M.9 and M.26 are susceptible to diseases such as fire blight (*Erwiniaamylovora*) and replant disease, which has led to the development of more resistant rootstock series like the Geneva rootstocks (Fazio *et al*., 2015). Dwarfing rootstocks play a pivotal role in modern apple production systems by substantially reducing tree vigour and ultimate canopy size, thereby enabling a marked increase in planting density (Ferree et al., 1993; Hampson et al., 2002, 2004a, 2004b; Robinson et al., 1991). Contemporary high-density orchards typically accommodate between 1,200 and 7,000 trees per hectare. Although such intensive systems often result in reduced yield on a per-tree basis, they significantly enhance productivity per unit area (Hampson et al., 2002, 2004a, 2004b). This improvement is primarily attributed to greater cumulative light interception over both annual and orchard lifespans, as well as more efficient light distribution within the canopy (Ferree et al., 1993; Robinson and Lakso, 1991; Robinson et al., 1991; Webster et al., 2000).

Despite the well-established economic advantages of high-density planting systems (Robinson et al., 2007), certain limitations persist, particularly concerning the susceptibility of specific dwarfing rootstocks to rootstock blight. This condition represents a distinct phase of Fire blight, a destructive disease caused by the bacterium Erwinia amylovora (Winslow et al.), which commonly affects members of the Rosaceae family (Vanneste and Eden-Greene, 2000). Fire blight can impact multiple developmental stages of the tree, and severe outbreaks may result in substantial economic losses due to reduced yields and the need for tree replacement.

While fire blight is most frequently associated with blossom and shoot infections, the rootstock phase has emerged as a significant concern, particularly in young orchards established on dwarfing rootstocks (Robinson et al., 2006). Rootstock blight typically develops when the pathogen enters the host through infected blossoms or shoots and subsequently spreads systemically via the vascular tissues to the rootstock, often without immediate external symptoms (Momol et al., 1998). In some cases, infection may also occur through wounds or infected rootstock suckers (Vanneste and Eden-Greene, 2000). Although the precise biological mechanisms underlying disease initiation and progression remain incompletely understood, it is well established that, once the pathogen colonises the rootstock, neither cultural practices nor chemical interventions are effective in preventing disease development (Norelli et al., 2003).

High-density apple production systems predominantly rely on the 'M.9' rootstock, which is widely recognised for its superior dwarfing capacity and high productivity. However, this rootstock is notably susceptible to rootstock blight. Under conditions conducive to severe fire blight outbreaks, tree mortality rates exceeding 50% have been reported in orchards established on 'M.9' (Ferree et al., 2002; Norelli et al., 2003; Robinson et al., 2006). Such extensive losses can have profound economic consequences, particularly given the high initial establishment costs associated with intensive orchard systems.

Nevertheless, the ‘M.9’ rootstock remains one of the most valuable and extensively utilised rootstocks for Malus × domestica due to its consistent ability to induce dwarfing, promote early bearing, and enhance fruit quality. Trees grafted onto M.9 have been reported to exhibit increased trunk girth, greater canopy spread, earlier fruit maturity, and improved fruit weight and firmness (Rifat Bhat et al., 2018). Given both its advantages and vulnerabilities, the development of new high-performance, disease-resistant rootstocks is essential to reduce dependence on M.9 and to ensure the long-term sustainability and profitability of high-density apple orcharding systems (Marini et al., 2006b).

Five-year-old ‘Fuji’ Fruit quality characteristics and aroma volatiles changed significantly in apples grown on four different rootstocks (MM-106, M-9, M-26, and MM-111). The largest fruits (212.2 g) with highest total soluble solids (18.40%) were obtained from the trees on M9 rootstock(Gur, E., 2019). A study by Kviklys*et al*., (2014) revealed that the total phenol content of the M9 rootstock was higher than the M26 rootstock.

b. MM-Series

The "MM" (Malling-Merton) series of apple rootstocks were developed in collaboration between the East Malling Research Station and the John Innes Institute in Merton, England, during the 1950s. This series was specifically bred to provide improved resistance to woolly apple aphid (*Eriosomalanigerum*), which was a significant problem for the previously developed M-series rootstocks (Cummins &Aldwinckle, 1983). The MM rootstocks are denoted by numbers such as MM.106 and MM.111, indicating their vigor and suitability for various orchard conditions.MM.106 is a semi-dwarfing rootstock, providing moderate vigor and being well-suited for a wide range of soil conditions. It is widely used in commercial orchards due to its good anchorage and early bearing properties. However, it is susceptible to crown rot (*Phytophthoracactorum*) in poorly drained soils (Ferree& Warrington, 2003). MM.111, on the other hand, is a more vigorous rootstock, offering greater tolerance to drought and replant disease, making it suitable for less fertile or dry soils. However, MM.111 can also exhibit excessive vegetative growth, which may require additional pruning and management (Rom & Carlson, 1987).Despite their advantages, MM rootstocks are not as widely used in modern high-density orchards due to their larger size and limitations in disease resistance compared to newer rootstocks like the Geneva series (Fazio *et al*., 2015). Findings reported by Bhat *et al.* (2018) indicated that apple cultivars grafted onto the MM.106 rootstock exhibited superior vegetative and reproductive performance, including increased plant height, higher percentage fruit set, and improved fruit retention. Similarly, Kebede Jobir (2016) evaluated the response of two apple cultivars, ‘Crispin’ and ‘Granny Smith’, to rootstocks differing in vigour (MM.106 and M.26), and demonstrated that all measured vegetative growth parameters—namely plant height, trunk girth, internode length, canopy spread, and branch number—were consistently greater in trees grafted onto MM.106 compared with those on M.26.

In a related study, J.A. Rather (2018) investigated the influence of rootstocks on a range of horticultural traits, including annual shoot extension growth, tree volume, trunk cross-sectional area (TCSA), fruit weight, fruit volume, and overall yield. The results revealed that these parameters were significantly affected by the choice of rootstock, with maximum vegetative growth recorded in trees grafted onto MM.106 as compared to those on M.9. While cultivar-specific responses are inherently governed by genetic factors, the influence of rootstock was clearly evident across all evaluated traits.

Furthermore, fruit quality attributes were also markedly improved in trees on MM.106. Fruits harvested from these trees exhibited significantly greater weight, volume, and yield relative to those produced on M.9 rootstock. Yield performance further substantiated these findings, with different cultivars grafted onto MM.106 producing higher yields of 16.55 and 20.19 kg per tree, compared to 13.70 and 18.65 kg per tree, respectively, for those on M.9. Collectively, these studies underscore the strong influence of MM.106 rootstock in enhancing vegetative growth, fruit quality, and productivity in apple cultivation.

c. G-series

The "G" series of apple rootstocks, also known as Geneva rootstocks, were developed by Cornell University and the United States Department of Agriculture (USDA) to address challenges like disease resistance and adaptability in modern apple orchards (Robinson *et al*., 2011). These rootstocks offer enhanced resistance to fire blight (*Erwiniaamylovora*) (Johnson *et al*., 2001; Norelli*et al*., 2003), crown rot, and woolly apple aphid compared to traditional rootstocks like the Malling (M) series (Russo *et al*., 2007). Popular rootstocks in the G-series include G.11, G.41, and G.935, which are known for their dwarfing effects, high productivity, and cold hardiness (Fazio *et al*., 2015). They are well-suited for high-density orchards and are recommended for sustainable apple farming due to their reduced susceptibility to disease and improved fruit yields. Additionally, they offer good support for apple trees, reducing the need for staking in some cases (Fazio *et al*., 2015). Geneva rootstocks exhibit high cumulative yield efficiency in multiple size classes combined with enhanced disease and, in some cases insect, resistance (Autio*et al*., 2005a, 2005b; Cummins and Aldwinckle, 1983; Robinson *et al*., 2006). Norelli*et al*. (2003) determined ‘G.16’ and ‘G.30’ suffered 70% less rootstock blight-related tree mortality than either ‘M.26’ or ‘M.9’ in both inoculated and naturally infected field trials.The yield performance of the 'Galaxy' and 'Fuji Suprema' scions grafted on the G.056, G.202, G.213, G.814, G.896, G.969, M.9, and Marubakaido/M.9 rootstocks were evaluated. G.896 and G.814 stood out due to their superior annual and cumulative fruit yields, as well as to their greater yield regularity (Denardi*et al*., 2018).An intensive multileader apple rootstock orchard trial was established in Trento province, Northern Italy, using dwarf (‘M.9-T337’) and semidwarf rootstocks (‘G.935’, ‘G.969’, and ‘M.116’) and ‘Gala’, ‘Golden Delicious’, and ‘Fuji’ as the scion cultivars. Trees were trained to Biaxis (‘M.9-T337’) and Triaxis systems (‘G.935’, ‘G.969’, and ‘M.116’) with a tree density of 3175 trees and 2116 trees per hectare, respectively, and with a uniform axis (leader) density of 6348/ha. Comparisons across all training systems by cultivar system showed that after 6 years (2019), trees of ‘Fuji’ and ‘Golden Delicious’ on ‘M.116’ were the largest trees followed by ‘G.969’, ‘G.935’, and ‘M.9-T337’. With ‘Gala’, trees on ‘G.969’ were of similar size as trees on ‘M.116’ and ‘G.935’. Trees of ‘Fuji’ on ‘G.935’ produced the highest yield followed by ‘G.969’, ‘M.116’, and ‘M.9-T337’. For ‘Gala’, trees on ‘M.116’ produced similarly as the ‘M.9- T337’, whereas with ‘Golden Delicious’, ‘G.969’ and ‘G.935’ had higher yields than ‘M.9-T337’. When comparing production per ground surface area (hectare) ‘G935’ had higher yield than ‘M.9-T337’ for all the cultivars in this trial. In addition, yield efficiency of ‘Fuji’ trees on ‘G.935’ was similar or even higher than trees on ‘M.9-T337’. Rootstock did not affect fruit size with ‘Fuji’. For Gala, fruit from ‘G.969’ were significantly larger than those on ‘M.116’. ‘Golden Delicious’ on ‘G.969’ produced smaller fruit compared with those on ‘G.935’. Fruit from trees on ‘M.9-T337’ had the lowest percentage of red color with ‘Fuji’ and the highest with ‘Gala’(Dalabetta*et al*.,2021).The Gala Select and Fuji Suprema cultivars were grafted onto ‘G.202’, ‘G.814’, ‘G.210’, and ‘G.213’ rootstocks in the Tall Spindle training system. In 2018/2019, total thinning was carried out to promote plant growth. In São Joaquim, partial thinning was carried out in 2019/2020 harvest of ‘Gala Select’. The rootstocks were divided into two groups based on vigor, for both areas and cultivars. ‘G.202’ and ‘G.213’ were 40% less vigorous than ‘G.210’ and ‘G.814’. For ‘Gala Select’, the extreme non-fallow condition mainly affected the vigor and productivity of ‘G.213’ in both areas. At the end of two harvests, ‘G.213’ was 17% less productive than ‘G.210’, contrary to what is observed in areas where the fallow period is respected. However, ‘G.213’ confirmed a greater yield efficiency, which was 27% higher than ‘G.210’. This suggests that a perspective of forecasting production for the third crop is higher for ‘G.213’ than for ‘G.210’. In the case of ‘Fuji Suprema’, the G.210 rootstock was the most productive in both areas. In São Joaquim, ‘G.202’ matched ‘G.210’ in productivity and efficiency as it sprouts better in colder regions. Considering the fruit quality, ‘G.213’ anticipated the maturation with fruits of larger size and higher total soluble solids (TSS) in both areas and cultivars, making it possible to anticipate the harvest (Rufato*et al*.,2021). The apple cultivar ‘Topaz’ was evaluated on a range of rootstocks, including M.9 (clone T337) with the interstem ‘Summerred’, G.11, CG.13, G.16, G.41, G.202, M.7, and MM.111, under organic production conditions over a nine-year observation period. Tree performance, vigour, and productivity were systematically assessed to determine the suitability of these rootstocks for sustainable orchard systems. Among the tested rootstocks, G.11 and G.41 demonstrated particularly favourable performance. Although tree losses associated with crown rot, caused by Phytophthora cactorum, were relatively high due to the inherent susceptibility of the ‘Topaz’ cultivar, both G.11 and G.41 still produced encouraging results when compared with the standard M.9 rootstock with interstem. G.11 exhibited growth characteristics comparable to those of M.9 but produced a higher fruit yield, indicating its potential as a productive alternative in organic systems. In contrast, G.41 displayed approximately 10% greater vegetative vigour while maintaining favourable yield performance. This balance between vigour and productivity suggests that G.41 is particularly well suited for replant situations, where enhanced growth capacity is often desirable. Overall, these findings highlight the potential of selected Geneva rootstocks, especially G.11 and G.41, as viable alternatives to traditional rootstocks in organic apple production, offering improvements in yield and adaptability despite challenges associated with disease susceptibility (Spornberger, 2020).

The resistance of the widely used commercial rootstocks M.26 and M.9, together with promising elite Geneva (G and CG) rootstocks, was systematically evaluated against a range of biotic stress factors. These included important soil-borne pathogens such as Phytophthora root rot caused by Phytophthora cactorum, white root rot caused by Rosellinia necatrix, and southern blight incited by Athelia rolfsii. In addition, resistance to the economically significant pest woolly apple aphid was also assessed. On 27 February 2019, unworked rootstock plants were lifted from stool beds, transplanted into 2-L containers, and subsequently maintained under controlled greenhouse conditions to facilitate uniform evaluation. The results demonstrated notable variation in resistance among the tested rootstocks. In the case of *P. cactorum*, the M.9 rootstock exhibited the highest level of resistance, whereas CG5087 and G935 showed comparatively lower resistance. With respect to *R. necatrix*, differences in susceptibility among the rootstocks were relatively minor; however, the Geneva (G and CG) series generally exhibited a trend towards lower susceptibility compared to the traditional Malling (M) series. These findings suggest that, while M.9 retains specific advantages in resistance to certain pathogens, the Geneva rootstocks may offer broader resilience against soil-borne diseases, thereby representing valuable alternatives for sustainable apple rootstock development (Choi et al., 2021).

An experiment was conducted under both polyhouse and field conditions over a three-year period (2013–2015) to evaluate the resistance of relatively less-studied apple rootstocks, including Paron (*Malus baccata* var. *himalacia*), alongside commonly cultivated regional rootstocks such as MM 106, MM 111, M 9, and Srinagar crab, against white root rot caused by Dematophora necatrix. Under controlled polyhouse conditions, Paron demonstrated a high level of resistance to the pathogen, recording the lowest mortality rate (15.33%) even at the highest inoculum concentration (10 g kg^{-1} soil) in pot culture. In contrast, all other tested rootstocks exhibited complete (100%) mortality at this inoculum level, indicating pronounced susceptibility.

Field evaluations further substantiated the superior resistance of Paron. Notably, no wilting symptoms were observed in the scion cultivar grafted onto this rootstock even after 60 days of pathogen inoculation. Moreover, Paron exhibited minimal disease-associated symptoms, including limited leaf bronzing and inward cupping (3.25%), low defoliation (3.50%), and reduced necrotic lesions in bark (21 mm), wood (17 mm), and vascular tissues (23 mm). Based on these observations, Paron was classified as resistant, as evidenced by its significantly lower disease severity index (4.35%) and minimal impact of pathogen inoculation on both above- and below-ground plant components. In contrast, Srinagar crab was identified as highly susceptible, exhibiting the greatest disease severity (69.80%) among the tested rootstocks (Kumar et al., 2019). These findings highlight the potential of Paron as a promising rootstock for managing white root rot in apple cultivation, particularly under conditions conducive to pathogen development.

d. B Series:

The **Budagovsky (B) series apple rootstocks** were developed at the Michurinsk University of Agriculture in Russia to enhance cold hardiness and other beneficial characteristics for apple trees (Cummins &Aldwinckle, 1983). The B series rootstocks are known for their distinctive red leaves and include different types, such as B.9, B.10, and B.118, each with varying levels of vigor and adaptability.**B.9** is a dwarfing rootstock and is widely used as an alternative to M.9, particularly in colder climates. Trees grafted onto B.9 are about 25-35% smaller than those on M.9 EMLA, with advantages such as early fruit ripening and resistance to fire blight and collar rot as they mature (Fazio *et al*., 2015; Penn State Extension, 2023). Due to its compact size, B.9 is suitable for high-density orchards but requires additional tree support for stability (extension.org).**B.10** is similar to B.9 in terms of dwarfing capability and yield efficiency but offers additional stress tolerance and good root anchorage, making it another valuable option for cold climates (Penn State Extension, 2023) (extension.org).**B.118** is a semi-dwarfing rootstock that is more vigorous and suitable for areas with low soil fertility or for spur-type apple varieties such as Fuji and Macintosh. It is highly cold-hardy, able to withstand temperatures as low as -18.4°F, and offers good resistance to fire blight. However, it can be susceptible to Phytophthora root rot in poorly drained soils (Cummins &Aldwinckle, 1983; Penn State Extension, 2023) (extension.org).The B series rootstocks are highly valued for their adaptability and cold-hardiness, making them an excellent choice for regions with severe winters, while also offering good disease resistance and tree performance in various orchard settings.Budagovsky 9 (B.9), Ottawa 3, Malling 9, and Malling 26 were the most fire blight susceptible rootstocks and Geneva 11, Geneva 65, Geneva 16, Geneva 30, Pillnitzer Au51-11, Malling 7, and several breeding selections were the most resistant (Norelli*et al*., 2003).

2.1 Characteristics of an Ideal Rootstock

1. An ideal rootstock should be easy to propagate (either vegetatively or by seeds) and must produce well, clean, easy-to bud or graft with upright stem.

Table 1. Characteristics of different apple rootstocks

Rootstock	Origin	Inventor/founder	Special Characteristics	Reference
M.9 (Malling 9)	East Malling Research Station, Kent, England.	East Malling Research Station.	**Size**: Produces very small trees (20-40% of standard size). **Precocity**: Very early bearing. **Yield**: High yield per acre due to high-density planting. **Support**: Requires permanent support. **Soil**: Prefers well-drained soil.	Crassweller, R., and J. Schupp. 2018
M.26 (Malling 26)	East Malling Research Station, Kent, England.	East Malling Research Station.	**Size**: Slightly larger than M.9 (30-50% of standard size). **Precocity**: Early bearing. **Yield**: Good yield, suitable for high-density planting. **Support**: Requires support. **Soil**: Performs well invarious soils.	Crassweller, R., and J. Schupp. 2018
M.7 (Malling 7)	East Malling Research Station, Kent, England.	East Malling Research Station.	**Size**: Produces medium-sized trees (50-60% of standard size). **Precocity**: Intermediate bearing. **Yield**: Good yield, suitable for medium-density planting. **Support**: Usually does not require support. **Soil**: Tolerates heavier soils.	Gomez, P., & Martin, S. (2011).
MM.106 (Malling 106)	East Malling Research Station, Kent, England.	East Malling Research Station.	**Size**: Slightly larger than M.7 (70-80% of standard size). **Precocity**: Intermediate bearing. **Yield**: Good yield. **Support**: Does not require support. **Soil**: Tolerates heavier soils,high temperature and drought conditions.	Crassweller, R., and J. Schupp. 2018.
MM.111 (Malling-Merton 111)	East Malling Research Station and John Innes Institute, Merton, England.	Collaborative effort by East Malling Research Station and John Innes Institute.	**Size**: Produces larger trees (80-90% of standard size). **Precocity**: Late bearing. **Yield**: Lower yield per acre but high per tree. **Support**: Does not require support. **Soil**: Tolerates poor drainage and drought conditions.	Crassweller, R., and J. Schupp. 2018.
M.27 (Malling 27)	East Malling Research Station, Kent, England.	East Malling Research Station.	Very dwarf	Crassweller, R., and J. Schupp. 2018.
Seedling (Antonovka, Dolgo)	Derived from seeds of the Antonovka apple variety.		**Size**: Produces very large trees (standard size). **Precocity**: Very late bearing. **Yield**: Lower yield per acre but high per tree. **Support**: Does not require support. **Disease Resistance**: Generally more resilient to various diseases. **Soil**: Tolerates a wide range of soil types.	Nelson, S., & Lee, J. (2011).
G.41 (Geneva 41)	Cornell University's New York State Agricultural Experiment Station, Geneva, New York, USA.	Cornell University's New York State Agricultural Experiment Station.	**Size**: Produces small to medium trees (similar to M.9). **Precocity**: Very early bearing. **Yield**: High yield. **Support**: Requires support. **Soil**: Prefers well-drained soil. G.41 has higher yield efficiency and produces few root suckers, better suited to high pH soils.	Fazio et al. (2014).
G.935 (Geneva 935)	Cornell University's New York State	Cornell University's New York	**Size**: Produces medium-sized trees (similar to M.26), slightly larger	Crassweller, R., and J.

Rootstock	Origin	Inventor/founder	Special Characteristics	Reference
	Agricultural Experiment Station, Geneva, New York, USA.	State Agricultural Experiment Station.	than M26, efficiency as M9 **Precocity**: Early bearing. **Yield**: Good yield. **Support**: Requires support. **Soil**: Prefers well-drained soil.	Schupp. 2018.
G.890 (Geneva 890)	Cornell University's New York State Agricultural Experiment Station, Geneva, New York, USA.	Cornell University's New York State Agricultural Experiment Station.	Semi dwarfing, 50-60% the size of seedling rootstock , similar to M7 but more precocious	Crassweller, R., and J. Schupp. 2018.
G.969 (Geneva 969)	Cornell University's New York State Agricultural Experiment Station, Geneva, New York, USA.	Cornell University's New York State Agricultural Experiment Station.	Similar in size to M7 at 45-55% size of seedling rootstock	Crassweller, R., and J. Schupp. 2018.
G.65 (Geneva 65)	developed by Dr. Jim Cummins	Cornell University	Tree size once thought to be about that of M.9 is now considered to be closer to M.27, rootstock is difficult to propagate in nursery stool beds, susceptible to tomato ring spot virus and apple stem grooving virus.	Rob Crassweller,2023
G.16 (Geneva 16)	Released from Cornell University's breeding program.	Cornell University	Size between M.9 and M.26. susceptible to woolly apple aphid and powdery mildew, very sensitive to latent viruses in apple and should only be propagated with virus free scion wood on top.	Rob Crassweller,2023
G.214 (Geneva 214)	Developed by the Geneva Apple Rootstock Breeding Program.	Dr. Jim Cummins and Gennaro Fazio in Geneva, New York.	Trees need to be supported and produce a tree about 30-35% size of seedling with vigor and precocity similar to M.9 and M.26.	Rob Crassweller,2023
G.202 (Geneva 202)	Originated at Cornell University in the UnitedStates	The New YorkState AgriculturalExperiment Station in Geneva, New York	Semidwarfing rootstock that produces a tree slightly larger than M.26. It was developed from a cross of M.27 and Robusta 5. It is fire blight and Phytopthora resistant as well as having resistance to woolly apple aphids. G.202 was about 50 percent smaller than M.7 but had much greater production efficiency.	Rob Crassweller,2023
G.11 (Geneva 11)	second release of the Cornell breeding program	Cornell university	5% smaller than trees on M.9T337, but more productive. Has the advantage of being resistant to fire blight and crown rot as well as only rarely producing suckers or burr knots.	Rob Crassweller,2023
Geneva 210 (G.210)	originated from the rootstock breeding program at Cornell University's Geneva, New York location		similar in size to Malling 7 but more productive and precocious. semidwarfing rootstock that is resistant to fire blight (*Erwiniaamylovora*) and crown rot (*Phytophthora* spp.).	Rob Crassweller,2023
(G.30) Geneva 30	originated from the New York State Agricultural Experiment Station in Geneva, New York		The advantage of this M.7-size rootstock is early production, fewer burr knots, and less suckering.	Rob Crassweller,2023
(G.222) Geneva 222	originated from a planned cross in Geneva, N.Y.	Geneva apple rootstock breeding program	Semi-dwarfing rootstock is reported to be approximately 45-55% the size of seedling and needs to be supported. Trees on this rootstock are similar in vigor to M.7 but more precocious and productive with good cold hardiness; resistance to fire blight, *Phytophthora* root rot and wooly apple aphid.	Rob Crassweller,2023,Crassweller, R., and J. Schupp. 2018
B.9 (Budagovsky 9)	Michurinsk State Agrarian University, Russia.	Michurinsk State Agrarian University.	**Size Control**: Produces dwarf trees (30-35% of standard size). **Precocity**: Very early bearing, often in the second or third year. **Yield**: High yield potential per acre. **Cold Hardiness**: Excellent cold hardiness, suitable for harsh winters.	Crassweller, R., and J. Schupp. 2018

Rootstock	Origin	Inventor/founder	Special Characteristics	Reference
			Support Requirements: Requires support such as staking or trellising. **Soil Adaptability**: Performs well in various soil types, prefers well-drained soils. **Vigor and Root System**: Strong, fibrous root system; good nutrient uptake. **Compatibility**: Compatible with many apple varieties.	
B.118 (Budagovsky 118)	Michurinsk State Agrarian University, Russia.	Michurinsk State Agrarian University.	It is more vigorous than the other rootstocks in the series but still imparts the high degree of winter-hardiness. It propagates easily in stool beds and does not sucker. It has moderate resistance to fire blight but is susceptible to *Phytophthora*. Because of the vigor of the rootstock it is only recommended for spur strains of apple or in weak soil or replant situations.	Rob Crassweller,2023
P.2 (Polish Rootstock)	Poland.	Developed by researchers in Poland.	**Size Control**: Produces dwarf to semi-dwarf trees (40-50% of standard size). **Precocity**: Early bearing, typically within 2-3 years. **Yield**: High yield potential. **Cold Hardiness**: Excellent cold hardiness, suitable for cold climates. **Support Requirements**: May require support, especially under heavy crop loads. **Soil Adaptability**: Performs well in a variety of soil types, prefers well-drained soils. **Vigor and Root System**: Moderately vigorous root system with good anchorage. **Compatibility**: Compatible with a wide range of apple varieties.	Kowalski, J., & Kwiatkowski, M. (2011).
P.16 (Polish Rootstock)	Poland.	Developed by researchers in Poland.	**Size Control**: Produces dwarf trees (30-40% of standard size). **Precocity**: Very early bearing, often within 2-3 years. **Yield**: High yield potential. **Disease Resistance**: Good resistance to fire blight and other common apple diseases. **Cold Hardiness**: Excellent cold hardiness, suitable for cold climates. **Support Requirements**: Requires support, such as staking or trellising. **Soil Adaptability**: Performs well in various soil types, including well-drained soils. **Vigor and Root System**: Moderate vigor with a well-developed root system. **Compatibility**: Compatible with many apple varieties.	Szymanska, J., &Nowak, A. (2012).
P.22(Polish Rootstock)	Poland.	Poland.	**Size Control**: Produces very dwarf trees (20-30% of standard size). **Precocity**: Very early bearing, typically within 2-3 years. **Yield**: High yield potential. **Disease Resistance**: Good resistance to fire blight and other common	Szewczyk, A., &Makowski, S. (2013).

Rootstock	Origin	Inventor/founder	Special Characteristics	Reference
			apple diseases. **Cold Hardiness**: Excellent cold hardiness, suitable for cold climates. **Support Requirements**: Requires permanent support, such as staking or trellising. **Soil Adaptability**: Performs best in well-drained soils. **Vigor and Root System**: Less vigorous, compact root system. **Compatibility**: Compatible with a wide range of apple varieties.	

2. Good root system is prerequisite to provide adequate anchorage and support the scion tree.
3. It should have wider adaptability (soil as well as climatic), winter hardiness, salt tolerance, diseases and insect-pests resistance, dwarfing, precocity and heavy cropping effects to the scion cultivar.

Different rootstocks possess diverse properties such as resistance to cold, drought, salinity, pests & diseases, etc.and impart various effects like tree yield, production, productivity and fruit size on the scion cultivars ad described as below Table 1.

Table 2. Comparison of various apple rootstocks

Rootstock	**Planting Distance(m)**	**Production (kg/tree)**	**Training system**	**References**
M27	1.5x1.5	5-10	Central leader	Shengrui , 2019
M9	1.5x3	20-30	Tall spindle system	Robinson *et al*., 2013;Rufato*et al*., 2022
M7	3x3	40-60	Standard Orchard	Phillips (2005), Fazio & Robinson (2020)
M26	3.5x3.5-4	25-40	Slender Pyramid	Robinson *et al*., 2013
MM 106	3x3	50-70	Vertical Axis	Emine KÜÇÜKER, 2021
MM 111	3.5x3.5-4.5	60-80	Vertical Axe	*Baldwin & Healy,2016*
G11	1.5x3	15-25	Tall spindle system	Robinson *et al*., 2013;Shengrui , 2019
G30	3x3	40-60	Slender Pyramid or Tall spindle system	Robinson *et al*., 2013;Shengrui , 2019
G202	3x3	30-50	Tall spindle system	Shengrui , 2019
G210	3x3	40-60	Tall Spindle training system	Rufato*et al*., 2021
G890	3x3	40-60	Tall spindle system	Shengrui , 2019
G16	1.5x3	25-35	Tall spindle system	Shengrui , 2019
G41	1.5x3	30-50	Tall spindle system	Robinson *et al*., 2013
G65	1.5x1.5	30-50	Tall spindle system	Shengrui , 2019
G935	3x3	40-60	Tall spindle system	Robinson *et al*., 2013
G214	1.5x3	50-70	Tall spindle system	Shengrui , 2019
G969	3x3	30-50	Tall spindle system	Shengrui , 2019
P22	1.2 between trees	40-60	Small centre leader, Pyramid, Step-over, Patio-container tree	South Sound Fruit Society, 2024
Bud 9	2.5m between trees	20-30	Vertical axis	South Sound Fruit Society,2024

Table 3. Disease reaction of different apple rootstocks

Apple rootstock	**Reaction to**			**References**
	Root rot	**Crown rot**	**Fire blight**	
M 7	Moderate susceptible	Moderately susceptible	Moderately resistant	Acimovic*et al*., 2023
MM106	Susceptible	Susceptible	Susceptible	Pruthi*et al*., 2023; Du pont*etal*., 2019
M26	Moderately Susceptible	Moderate susceptible	Susceptible	Dupont*etal*., 2019
M9	Resistant	Resistant	Susceptible	Pruthi*et al*., 2023
M 27	Moderately resistant	Moderately resistant	Susceptible	Biggs *et al*., 2019
MM 111	Susceptible	Susceptible	Tolerant	Biggs *et al*., 2019 Crassweller, R. &Schupp, J. (2018).
G969	Resistant	Resistant	Very Resistant	Cummins *et al*., 2013,Fazio*et al*., 2018
G11	Tolerant	Tolerant	Resistant	Fazio *et al*., 2018
G30	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G202	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G210	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G890	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G16	Tolerant	Tolerant	Resistant	Fazio *et al*., 2018
G41	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G65	Resistant	Resistant	Resistant	Biggs *et al*., 2019 Norelli*et al*.,2007
G935	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G214	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
G222	Tolerant	Tolerant	Very resistant	Fazio *et al*., 2018
B 9	Moderately resistant	Moderately resistant	Moderately resistant	Acimovic*et al*., 2023, DuPont *et al*.,2019
B118	susceptible	Susceptible	Moderately resistant	Acimovic*et al*., 2023
P2	Resistant	Resistant	Susceptible	Biggs *et al*., 2019 Baritt*et al*., 2004
P22	Resistant	Resistant	Moderately susceptible	Biggs *et al*., 2019 Anonymous,2019

Table 4. Wooly apple aphid resistance of different apple rootstocks

Apple rootstock	Wooly apple aphid	Reference
M21, M20, M2, M109,M9 and M13	Susceptible	Thakur and Gupta, 1998 ,Mohan*et al*., 2022, Pruthi*et al*., 2023
M12, M16, M3, M4, M1, and M5	Less susceptible	Thakur and Gupta, 1998 ,Mohan*et al*., 2022
MM104, MM106	Moderately resistant	Thakur and Gupta, 1998 ,Mohan*et al*., 2022
MM101, MM114 and MM115	Very Resistant	Thakur and Gupta, 1998, Mohan*et al*., 2022
G 16	Moderately susceptible	Cummins et al 2002
G969,G890,G210, G214,MM 111	Resistant	Robinson *et al*.,2014, Pruthi*et al*., 2023
G11, G30,G935	No resistance	Fazio *et al*., 2018
G41, G213, G222, G202,	Highly resistant	Fazio *et al*., 2018

Table 5.Abiotic Stress Resistance:

Apple rootstock	Reaction to			References
	Drought	**Salinity**	**Cold**	
M 7	Moderate tolerance	Low tolerance	Not cold-hardy	South Sound Fruit Society, 2024
MM106	Resistant	Moderate tolerance	Not cold-hardy	Sun *et al*., 2022 South Sound Fruit Society, 2024
M26	Highly tolerant	Least tolerant	Moderate cold-hardy	South Sound Fruit Society, 2024 Hezema*et al*., 2021
M9	Less drought tolerant than MM 106	Moderate tolerance	Not cold-hardy	Aras and Keleş (2019). South Sound Fruit Society, 2024
M 27	Low tolerance	Low tolerance	Not cold-hardy	South Sound Fruit Society, 2024
MM 111	Highly tolerant	Moderate tolerance	Low cold hardiness	Atkinson *et al*., 1999
G969	High tolerant	Moderate tolerance	Low cold hardiness	South sound fruit society,2024
G11	Moderate	Moderate	Moderate cold-hardy	South sound fruit society,2024
G30	Moderate	Moderate	Slightly better than M.26	South sound fruit society,2024
G202	Highly tolerant	Moderate	Moderate	Choi *et al*., 2020
G210	High tolerance	High tolerance	Moderate cold-hardiness	Choi *et al*., 2020
G890	High tolerance	High tolerance	High cold hardiness	Choi *et al*., 2020
G16	Moderate tolerance	Moderate tolerance	Good cold hardiness, but not as cold-hardy as most other G-series rootstocks	South Sound Fruit Society, 2024
G41	Moderate tolerance	Most tolerant	Variable cold-hardiness	Hezema*et al*., 2021
G65	Moderate tolerance	High tolerance	Cold-hardy	South Sound Fruit Society, 2024
G935	Highly tolerant	Least tolerant	Highest root cold-hardiness	Choi *et al*., 2020 Hezema*et al*., 2021
G214	Highly tolerant	Moderate	Moderate	Choi *et al*., 2020
G222	Moderate tolerance	Moderate tolerance	High cold hardiness	Choi *et al*., 2020
B 9	Resistant	Most tolerant	Moderate tolerance	Sun *et al*.,2022 Hezema*et al*., 2021
B118	Moderate	Least tolerant	Moderate	Hezema*et al*., 2021
P2	Moderate	Moderate	Moderate	South sound fruit society, 2024
P22	Moderate	Moderate	Good cold-hardiness	South Sound Fruit Society, 2024

Table 6. Effect of Apple Rootstocks on Leaf and Fruit Mineral Nutrition

Rootstock Type	Effects on Mineral Concentration	References
M.26 (Semi-dwarf)	Higher accumulation of minerals (N, P, K, Ca, Mg) in leaves and fruits.	Kviklys*et al*., 2017
More Dwarfing Rootstocks	Higher leaf Ca content, lower Mg content; dwarfing rootstocks determined lower K, N, and Mg ratios to Ca.	Kviklys*et al*., 2017
Vigorous Rootstocks	Positive effect on fruit K and P content; higher K and P in fruits compared to dwarfing rootstocks.	Kviklys*et al*., 2017
B9	Spur leaves had 30% high Ca concentrations	Hirst and Ferree, 1995
M9	High mineral compound concentration (K, Na, Mg, Cu)	Kiczorowski*et al*., 2018
P2	High mineral compound concentration (K, Na, Mg, Cu).	Kiczorowski*et al*., 2018
P22	Highest mineral compound concentration (K, Na, Mg, Cu).	Kiczorowski*et al*., 2018

2.2 Influence of Rootstocks on Orchard Performance

Tree Vigor: Rootstocks significantly influence tree size and canopy architecture. Dwarfing rootstocks such as M9 produce compact trees suitable for high-density planting, while vigorous rootstocks produce larger trees requiring wider spacing.

Yield Efficiency: Rootstocks affect precocity and yield efficiency. Dwarfing rootstocks generally promote early fruiting and higher yield per unit canopy volume compared with vigorous rootstocks.

Fruit Quality: Rootstock selection influences fruit size, color development, sugar accumulation, and firmness. Improved nutrient uptake and balanced vegetative growth contribute to better fruit quality.

Disease Resistance: Some rootstocks provide resistance to major diseases such as:

- Fire blight
- Crown rot
- Woolly apple aphid

Geneva rootstocks have been particularly successful in improving disease resistance.

Tolerance to Abiotic Stresses
drought Rootstocks also influence tolerance to environmental stresses such as:

- salinity
- cold
- nutrient deficiency

Budagovsky and Geneva rootstocks have shown improved adaptability to such stresses.

2.3 Rootstock–Scion Interaction

The interaction between rootstock and scion plays an important role in determining tree performance. Rootstocks influence water and nutrient uptake, hormone signaling, and overall physiological processes within the grafted plant.

This interaction affects:

- tree growth and canopy development
- flowering and fruiting behavior
- stress tolerance

Understanding these interactions is essential for optimizing orchard productivity.

3. Conclusion

Apple rootstocks play a crucial role in determining orchard productivity, tree architecture, fruit quality, and tolerance to environmental stresses. The development of dwarfing and disease-resistant rootstocks has significantly improved modern apple production systems, particularly under high-density planting. Rootstocks such as those from the Geneva series represent important advances in breeding for disease resistance and stress tolerance. Future research should focus on understanding rootstock–scion physiological interactions and developing rootstocks adapted to changing climatic conditions and sustainable orchard management practices.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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